Department of Applied Mechanics

# Risk analysis in maritime transportation: principles, frameworks and evaluation

Floris Goerlandt

Aalto University

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# Risk analysis in maritime transportation: principles, frameworks and evaluation

**Floris Goerlandt**

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# Abstract

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**Abstract**

Risk analyses are widely used tools for supporting decision making. Nonetheless, many criticisms have been raised against the discipline of risk analysis, e.g. technical analyses having a narrow focus, poorly examined claims of the ability of accurately measuring risk and lack of standards for quality assurance and risk analysis evaluation. In response to these criticisms, calls have been made for increased focus on these and other foundational issues, both in the general risk analysis discipline and in the various application areas.

This thesis answers these calls for research addressing the underlying concepts and principles of risk analyses, which are approached through applications focusing on the accidental risk of maritime transportation. Focusing first on a set of foundational issues underlying waterway risk analyses, it is established that many different definitions, perspectives and scientific approaches co-exist in the application area. Through two case studies of reliability of maritime risk models, previous research claiming that risk models provide unreliable decision support, are confirmed for some maritime applications, thus confirming the need for focusing on risk related principles.

Subsequently, a set of principles is presented, addressing concepts and terminology, risk and prediction, risk model use and the consideration of uncertainty and bias. A framework is introduced to communicate the scientific principles adhered to in a specific risk analysis.

Following this, the principles are translated in two risk analysis frameworks: one for policy-oriented and one for operational risk analysis; the first leading to a quantitative and the second to a qualitative risk characterization. In both, risk is understood as a concept referring to the possible but uncertain occurrence of a situation where something of human value is at stake.

Risk models are used as putting forward an argument based on available evidence, as a tool for communication between stakeholders and as a platform for thinking. Uncertainties and value-laden biases are assessed, and some tools for communicating these are introduced. Both frameworks are illustrated by extensive case studies. The first concerns accidental risk of oil spills from tanker collisions in the Gulf of Finland. The second focuses on a risk-informed ship-ship collision alert system.

A final issue addressed in the thesis concerns the evaluation of a risk analysis, i.e. principles and criteria for establishing credibility. An integrated framework for this is developed, addressing model use, model plausibility, value-related validity and process-related validity. Specific evaluation criteria are proposed and a selection of these is applied in the presented case studies.

**Keywords** Risk analysis, foundational issues, waterway risk, collision alert system

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# Preface

This thesis is based on work carried out at the Maritime Risk and Safety research group at the Department of Applied Mechanics in Aalto University. The work has been conducted within the RescOp and WINOIL projects, which are co-funded by the European Union, the Russian Federation and the Republic of Finland, and the project FAROS, funded by the European Union under the FP7-program. Financing for finalizing the thesis has been received from Merenkulun Säätiö. This financial support is gratefully acknowledged.

First, I would like to warmly thank my supervisor and advisor, prof. Pentti Kujala. His support and encouragement was important during the entire period of my doctoral studies. I particularly appreciate how Pentti has allowed me the freedom to pursue my own research interests, over and beyond the needs from the projects I have been involved in. I also sincerely thank my second advisor, dr. Jakub Montewka. His support, guidance and devoted enthusiasm for research have been very valuable during the entire process. I am also thankful to my final co-author Vladimir Kuzmin for his contributions to the research. Special thanks also go to prof. emer. Petri Varsta for reading the thesis draft, and for providing comments which helped to more clearly articulate the flow of ideas. I also want to express my gratitude to prof. emer. B.J.M. (Ben) Ale and dr. Xiaobo (Bob) Qu who acted as the pre-examiners of this thesis and provided useful remarks, and to prof. Terje Aven for accepting to be opponent despite numerous other commitments and activities.

I would also like to thank my department colleagues, especially but not only the current and former post-graduate students from the Maritime Risk and Safety research group, for the peer support, practical help and for creating a pleasant work environment. The secretaries deserve a special mention for solving many practical daily problems, as well as the staff at the Kotka Maritime Research Centre for facilitating the projects in which the research was done.

Finally, I am thankful to my family and friends, especially to my wife Hanna for the continuous support. I particularly appreciate her dedication to and care for the increasingly busy household during these thesis years. I thank my children Leila, Sonja, Boris and Alma for the happiness and joy they have brought to my life, and for tidying up their toys before going to bed.

Espoo, Wednesday, 20 May 2015

Floris Goerlandt

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# List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their Roman numerals.

**PI.** Goerlandt, Floris; Montewka, Jakub. 2015. Maritime transportation risk analysis: review and analysis in light of some foundational issues. Reliability Engineering and System Safety, volume 138, pages 115-134. ISSN 0951-8320. DOI 10.1016/j.ress.2015.01.025.

**PII.** Goerlandt, Floris; Kujala, Pentti. 2014. On the reliability and validity of ship-ship collision risk analysis in light of different perspectives on risk. Safety Science, volume 62, pages 348-365. ISSN 0925-7535. DOI 10.1016/j.ssci.2013.09.010.

**PIII.** Goerlandt, Floris; Montewka, Jakub. 2015. A framework for risk analysis of maritime transportation systems: a case study for oil spill from tankers in a ship-ship collision. Safety Science, volume 76, pages 42-66. ISSN 0925-7535. DOI 10.1016/j.ssci.2015.02.009.

**PIV.** Goerlandt, Floris; Montewka, Jakub; Kuzmin, Vladimir; Kujala, Pentti. 2015. A risk-informed ship collision alert system: framework and application. Safety Science, volume 77, pages 182-204. ISSN 0925-7535. DOI 10.1016/j.ssci.2015.03.015.

# Author's Contribution

**Publication I:** Maritime transportation risk analysis: review and analysis in light of some foundational issues

The author developed the idea, prepared the framework for analysis, carried out the analysis and was the main contributor to the manuscript. Montewka provided valuable comments and suggestions.

**Publication II:** On the reliability and validity of ship-ship collision risk analysis in light of different perspectives on risk

The author developed the idea, carried out the analyses for the case study, and was the main contributor to the manuscript. Kujala provided valuable comments and suggestions.

**Publication III:** A framework for risk analysis of maritime transportation systems: a case study for oil spill from tankers in a ship-ship collision

The author developed the framework, constructed the model, carried out the analyses and evaluations for the case study, and was the main contributor to the manuscript. Montewka provided valuable comments and suggestions.

**Publication IV:** A risk-informed ship collision alert system: framework and application

The author developed the idea, prepared the expert elicitations, implemented the model, carried out the analyses and evaluations for the case study, and was the main contributor to the manuscript. Montewka assisted in the expert elicitation and contributed to the manuscript. Kuzmin assisted in the expert evaluation of the developed model and contributed to the manuscript. Kujala provided valuable comments and suggestions.

# Original features

This thesis aims to contribute to selected foundational issues within the application area of maritime transportation Risk Analysis. Focus is on the principles underlying risk analysis applications as tools tool for informing decisions, on proposing frameworks for building applications, and on principles and methods for evaluating these. The applications concern policy-oriented maritime waterway risk analysis and operational risk analysis in a collision avoidance context. The following features of this thesis are believed to be original:

1. A detailed analysis is conducted of adopted risk definitions, perspectives and scientific approaches to risk analysis in applications addressing accidental risk in maritime waterways. Dependencies between definitions, perspectives and approaches are identified. [**PI**]

2. The reliability of policy-oriented and operational maritime transportation risk analysis applications is systematically studied. [**PII**, **PIV**]

3. A two-stage policy-oriented risk analysis framework for maritime transportation systems is developed, including a risk-theoretical basis linked with the applied measurement tools. Tools for contextualizing the quantitative risk picture are proposed. [**PIII**]

4. A two-stage risk analysis framework for ship collision alert systems in an operational context is developed, including a risk-theoretical basis linked with the applied measurement tools. A framework for operationalizing the construct "ship-ship collision risk" is proposed. [**PIV**]

5. A Bayesian Network model for oil spill risk analysis for tanker collisions is developed, focusing on the potential occurrence of spills of various sizes [**PIII**]

6. A Fuzzy Expert System based model is developed for providing risk-informed ship-ship collision alerts in an open sea area [**PIV**]

7. Principles and methods for evaluating policy-oriented and operational risk analysis applications in maritime transportation systems are proposed [**PIII**, **PIV**]

# Special terms

**maritime transportation** an activity in which ships transport goods from one location to another over sea or waterway areas

**operational risk analysis** a risk analysis which is continuously performed to support decision making in an ongoing operation which may require fast decision making and action

**policy-oriented risk analysis** a risk analysis which is performed at a given point in time or is performed periodically, to support a decision in a policy context which has implications to investments and societal concerns

**principle** a fundamental proposition that serves as a foundation for a system of beliefs or for a chain of reasoning

**Risk Analysis** the scientific risk discipline, concerned with developing concepts, principles, frameworks and models for analysing risk (Aven, 2012a)

**risk analysis** A specific case study in which risk is analysed (Aven, 2012a)

**risk analysis evaluation** a process of building confidence in a given risk analysis, a process of appraising or valuing the analysis and its results

**risk analysis framework** a basic structure, a set of ideas, mechanisms and tools that provide support for performing a risk analysis

**risk concept** the 'general idea' of what risk is as a constituent of thought

**risk definition** the result of an intellectual activity to delineate a meaning of the risk concept

**risk perspective** a way to describe risk, a systematic manner to analyse and make statements about risk

**reliability** the extent to which a measurement procedure leads to the same result when the measurement is repeated

**scientific approach to Risk Analysis** a set of principles adhered to as a basis for performing a risk analysis, in particular whether realist, constructivist or proceduralist foundations are adopted

**validity** the extent to which a measurement procedure adequately describes the concept one intends to describe

# Abbreviations

| | |
|---|---|
| BN | Bayesian Network |
| BSQ | background situational quality |
| CAS | collision alert system |
| COLREGS | international regulations for preventing collisions at sea |
| DCPA | distance at closest point of approach |
| FES | fuzzy expert system |
| FSA | formal safety assessment |
| FSQ | foreground situational quality |
| MF | membership function |
| QRA | quantitative risk analysis |
| SQ | situational quality |
| TCPA | time to closest point of approach |
| VTS | vessel traffic service |

# 1. Introduction

## 1.1 Motivation: Risk Analysis as an unsettled scientific discipline

Risk analyses are widely used for decision support. In the maritime application area, many risk analysis approaches and models have been proposed for various purposes. This includes regulatory decision making concerning ship design and equipment (IMO, 2008, 2007), ship design (Klanac and Varsta, 2011; Papanikolaou, 2009), prevention and mitigation of maritime transportation accidents in waterways (Li et al., 2012; Özbaş, 2013) and operational collision avoidance (Statheros et al., 2008; Tam et al., 2009). Much research has been dedicated to developing advanced mathematical methods for risk analysis, and many applications for specific problems have been presented in the literature.

Nonetheless, risk analysis, and especially quantitative risk analysis (QRA), has been widely criticised, see Table 1.

**Table 1.** Summary of some main criticisms concerning risk analysis

| Criticism | References |
|---|---|
| Narrow focus of technical analyses: lack of inclusion of public perception and consent to procedure. | Kermisch (2012), Kunreuther and Slovic (1996), Wolff (2006) |
| Abuse of risk analyses to serve interests of business and government agencies, by suppressing uncertainty and adjusting assumptions to meet predefined risk acceptance criteria. | Shrader-Frechette (1993), O'Brien (2000), Aven (2011) |
| Causal accident theories underlying technical analyses are simplistic in complex systems, due to risk compensation and feedback. | Adams (1995), Leveson (2012), Stringfellow (2010) |
| Little academic scrutiny about efficacy for engineering safer systems. | Rae et al. (2014) |
| Poorly examined claims about ability to accurately measure risk. | Rae et al. (2014) |
| Lack of scientific understanding of and standards for quality assurance / evaluation of risk analysis: "peer review" lacks evaluation criteria. | Cumming (1981), Rae et al. (2014) |

In response to these criticisms, there has been and is ongoing research to strengthen the foundations of Risk Analysis. This amongst other concerns creating meta-theoretical frameworks for classifying different risk problems (Klinke and Renn, 2002; Rosa, 1998), attempts at clarifying a number of conceptual foundations of the field (Aven and Renn, 2009; Johansen, 2010; Rosa, 2010), proposing alternative scientific platforms for risk analysis (Aven, 2011; Hermansson, 2005) and proposals for evaluating risk analyses (Busby and Hughes, 2006; Rosqvist and Tuominen, 2004).

Nonetheless, these and many issues need further research (Aven, 2012a), and calls have been made to extend the research on foundational issues to the application areas (Aven and Zio, 2014). The need for more research on Risk Analysis *per se* has also been voiced in the maritime application area, as focus on these issues has been rather limited in the maritime field (Psaraftis, 2012).

## 1.2 Objectives and structure of the thesis

The overall objective of this thesis is to contribute to some foundational issues within the application area of maritime transportation risk analysis. Focus is on principles underlying a risk analysis as a tool for informing decisions, on developing frameworks for performing risk analyses, and on principles and methods for evaluating risk analysis applications. Focus is on policy-oriented waterway risk analysis (i.e. supporting societal decisions) and operational risk analysis in a collision avoidance context (i.e. supporting decisions in an ongoing operation). The specific objectives are:

**Objective 1**: Investigate which definitions, perspectives and scientific approaches to Risk Analysis have been adopted in maritime waterway risk analysis applications, and their relations.
**Objective 2**: Investigate the reliability of selected waterway risk analysis applications and risk models for ship collision alert systems.
**Objective 3**: Present a set of principles as a basis of subsequently developed risk analysis frameworks. These address terminology and adopted understanding of key concepts, risk modelling in relation to prediction, risk model use and the consideration of uncertainty and bias. These principles intend to clarify the adopted scientific approach to risk analysis.
**Objective 4**: Propose frameworks for waterway risk analysis and risk analysis in a collision avoidance context, and present applications to illustrate the rationale.
**Objective 5**: Contribute to the research on the evaluation of risk analyses, addressing both the principles and practical tools.

The links between these objectives, the publications (PI to PIV) and the structure of the thesis summary (section numbers) are shown in Figure 1.

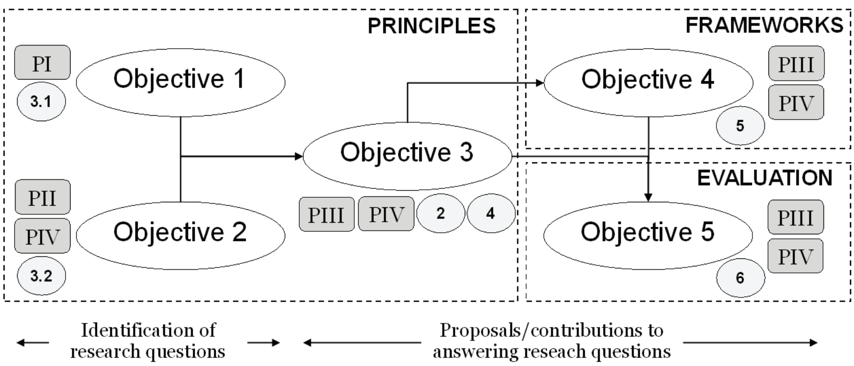



**Figure 1.** Relations between research objectives, publications and structure of the thesis

Objective 1 primarily aims to identify a need to focus on the underlying principles of risk analyses in the maritime application area. Based on this, Objective 3 focuses on proposing a conceptual basis for Risk Analysis, and on the need for systematically considering uncertainties and biases in applications.

Objective 2 supports the need to focus on underlying principles by performing two reliability analyses of waterway risk applications and risk models for collision alert systems. The findings lead to the questions of how risk models may be justifiably used, which addressed in Objective 3 and how risk analyses can be evaluated, addressed in Objective 5.

In Objective 4, frameworks are proposed which translate the principles addressed in Objective 3 to practical methods and tools for performing a risk analysis. Objective 5 is closely linked to Objective 3 and Objective 4.

In the summary, Section 2 provides a background for the research topics. A general introduction is given to different foundational views on Risk Analysis, and the concepts of reliability, validity and evaluation are outlined. A brief review is given of previous research on these issues, focusing on the maritime application area. Section 3 summarizes the main research results related to the diffuse state of the scientific maritime risk analysis application area (PI), the results of the research addressing reliability (PII and PIV), and formulates a number of research questions. Section 4 establishes the principles underlying the frameworks of PIII and PIV. Section 5 outlines the main features of the frameworks presented in PIII and PIV, and briefly shows the developed applications. Section 6 combines the approaches to risk analysis evaluation presented in PIII and PIV. Section 7 concludes.

## 1.3 Limitations

Maritime Risk Analysis is a very broad research area. This thesis focuses only on Risk Analysis in maritime transportation, and in particular on waterway risk analysis applications and on risk analysis in a collision avoidance context. While the results may be more widely applicable also to other problems, this is not explicitly claimed or further addressed.

While a coherent set of principles of Risk Analysis is addressed in this thesis, many other foundational issues require attention. Much more research is needed on topics such as understanding the concepts underlying the discipline, the implications of and ways to address uncertainty in complex systems, the role of values in Risk Analysis, ways to represent and communicate risk analysis results, the role of risk science in societal decision making, and many more, see Psaraftis (2012) and Aven and Zio (2014).

It is acknowledged that other risk analysis frameworks for the addressed application areas may be feasible. No claims are made that the presented frameworks are the only possible ones. The ambitions are more modest to devise frameworks with clearly articulated underlying principles, answering calls to this effect (Aven and Zio, 2014; Psaraftis, 2012).

Given the very limited research dedicated to how to evaluate risk analyses, the principles and tools for this should be considered as an exploratory attempt to contribute to this research area.

# 2. Background

## 2.1 Scientific approaches to Risk Analysis

A central issue in this thesis is the differing views on the scientific basis of Risk Analysis[2]. This has been addressed in the Risk Analysis literature, but no research is known in the maritime application area where this is addressed. Because this is important for the objectives of Section 1.2, a brief outline is given.

There are three prototypical approaches: realist, constructivist and proceduralist. While variations exist (see PI), these prototypes are useful to understand the philosophical schisms underpinning the discipline.

### 2.1.1 Realist approaches

Risk realists typically consider risk as a physically given attribute of a system, which can be characterized by objective facts. Work is performed under the presumption that the quantities resulting from technical analyses are a representation or an approximation of an absolute truth. Risk management decisions are considered rational to the extent they are based on the objective, non-personal factors of technical analysis (Bradbury, 1989; Shrader-Frechette, 1991; Thompson and Dean, 1996). Thus, realist approaches to Risk Analysis rely exclusively or primarily on data and models from engineering or natural sciences. Expert judgment, if applied, is seen as an objective representation of an underlying truth, totally determined by evidence. This view is succinctly expressed by Kaplan, who understands risk as a set of scenarios, probabilities and consequences (1997, p. 414):

> This idea of "objectifying" the so called subjective probability has major implications. It resolves the historical controversies, and it shows us the how to put Risk Analysis on a totally solid conceptual foundation. It opens the way to what we can call "evidence-based" risk assessment and "evidence-based" decision

[2] It is worth reflecting on the fact that various authors have expressed concerns about Risk Analysis being a science at all. Two editorials in the first edition of the Risk Analysis journal express serious reservations to its scientific nature (Cumming, 1981; Weinberg, 1981). More recently, arguments have been made that it is scientific "when understood as consisting primarily of (i) knowledge about risk-related phenomena, processes, events, etc., and (ii) concepts, theories, frameworks, approaches, principles, methods, and models to understand, assess, characterize, communicate, and manage risk, in general and for specific applications (the instrumental part)." (Hansson and Aven, 2014, p. 1181)

> making. In regulatory and public decision making it shows us how, quantitatively, to “*Let the Evidence Speak!*” not the opinions, personalities, moods, politics, positions, special interests, or wishful thinking!

This reification of risk has several implications. First, understanding risk as a kind of physical quantity, the focus in risk analyses is on the calculated numbers (often probabilities). From this, there typically is a strong link between the risk quantification and decision criteria. This can be either through risk acceptance criteria, or through mathematical procedures such as maximizing expected utility. Kaplan (1997) and De Rocquigny et al. (2008) propose such risk-based decision frameworks. Second, a sharp distinction is claimed to exist between the facts of technical analysis and the non-epistemic values[3] inherent in decision making (Bradbury, 1989; Shrader-Frechette, 1991). Finally, contextual dimensions such as controllability, fear, the voluntariness of exposure and emotions with respect to the possible occurrences are seen as accidental and not part of the risk concept *per se* (Thompson and Dean, 1996).

### 2.1.2 Constructivist approaches

Risk constructivists reject the idea that risks exist as some absolute quantity independently of the people assessing and experiencing them. Their starting premise is that risk primarily involves social processes. Hence, their focus shifts from (probabilistic) quantifications to the assessor/perceiver of risk, expert as well as layperson (Bradbury, 1989; Shrader-Frechette, 1991; Thompson and Dean, 1996). Several variations of this view exist. One manifestation is clearly expressed by Otway and Thomas (1982, p. 70):

> It is clear that truths do not exist independently of *people*, whether taken to be individuals, significant social groups in the general public, professional or political/industrial groups. […] Once the criterion of an absolute truth is abandoned, then surely no one can avoid the inference *that people see the world differently* and that these differences emerge from different experiences of differently constructed social worlds.

Another constructivist view is expressed by Aven and Renn, defining risk as “the uncertainty about and severity of the events and consequences/outcomes of an activity with respect to something that humans value” (2009, pp. 8–9):

> In our concept, risk does not exist independent of the assessor, as the uncertainties need to be assessed by somebody. […] Risk according to our definition requires a mental construction of the uncertainty (knowledge) dimension […] ‘Uncertainty’ is not real, it is a construct of a human imagination to cope with potential future outcomes that can become real. […] Emphasizing the subjective

[3] Non-epistemic values are values of a moral, political or aesthetic nature, i.e. values which have no relevance to determining whether a claim is true but stem from a reflective consideration of what is good in a given context (Wandall, 2004).

> and constructive nature of uncertainty does not imply, however, that these constructs are arbitrary or not subject to scientific scrutiny.

Some constructivists adhere to a broad, polythetic understanding of risk, and include perceptual factors such as controllability, fear, the voluntariness of exposure, emotions and procedural issues such as liability and trust in the risk concept, apart from probabilities and events/consequences (Kermisch, 2012; Rayner, 1992; Slovic, 1999; Wolff, 2006). Thus, these characteristics are all part of the risk concept, but none of these are essential for describing risk.

Another feature of many constructivist approaches to Risk Analysis is the rejection of a complete separation between facts and values, stressing the value-ladenness of risk analyses: it is argued that problem framing, choice of risk metrics and the types of assumptions made are no value-neutral exercises (Bohnenblust and Slovic, 1998; Bradbury, 1989; Hansson, 2010; Shrader-Frechette, 1991).

The subjective nature of risk has implications for how risk is managed. First, the risk decision process does not exclusively rely on the quantitative results of technical analysis. Perceptual and other qualitative factors are considered as well in the decision (Bohnenblust and Slovic, 1998; Bradbury, 1989). Second, constructivist approaches do not typically apply strict risk acceptance criteria or mathematical decision procedures such as maximization of expected utility: a process of looking beyond such mathematical tools is needed (Aven and Vinnem, 2005; Hartford, 2009).

### 2.1.3 Proceduralist approaches

Some authors have argued that in democratic societies, the fairness of the distribution of risks and benefits related to a given activity are important aspects of consistent risk management, which is often linked to the fairness of risk analysis and decision making procedures (Fiorino, 1989; Hermansson, 2005).

The requirement of including risk-affected parties in the risk analysis process has been argued for on ethical grounds (Shrader-Frechette, 1991), and several mechanisms have been suggested for public participation in decision making (Fiorino, 1990; Hermansson, 2010; Renn et al., 1993).

In procedural approaches, different stakeholder groups such as scientists, domain experts, risk-affected lay persons and decision makers take part in a deliberative process. Thus, risk is characterized and decision options evaluated by explicitly accounting for facts, expert judgments and stakeholder values. Such an approach to analysing risk is known as an analytic-deliberative process, in which rationality is defined through adherence to democratic principles (Douglas, 2009; Shrader-Frechette, 1991; Stern and Fineberg, 1996).

## 2.2 Reliability, validity and evaluation of risk analysis

### 2.2.1 Outline of the concepts

Reliability and validity relate to measurement methods, addressing two essentially different properties. Reliability is concerned with the question in how far a measurement leads to the same result when the measurement is repeated, whereas validity concerns the question to what extent the measurement appropriately describes the concept one intends to describe (Carmines and Zeller, 1979; Trochim and Donnely, 2008). Figure 2 illustrates the concepts using the analogy of a target. A valid measurement results in an outcome close to the bulls-eye, either directly or as an average of repeated measurements. A reliable measurement results in outcomes which are closely clustered, while unreliable measurement involves large scatter.

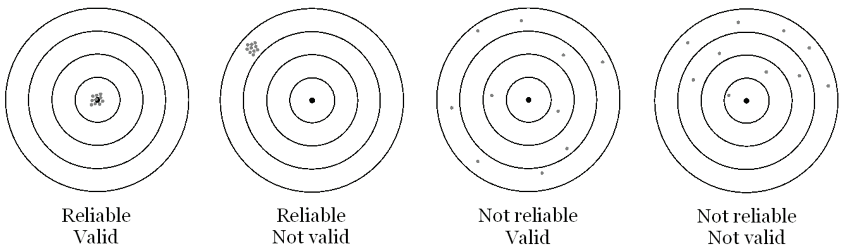



**Figure 2.** Illustration of the concepts of reliability and validity in a measurement context

Risk analysis evaluation concerns the process of building confidence in a given risk analysis. It can be defined as "[...] an independent peer review process consolidating the decision-maker's confidence in the results [...] of risk assessment"[4] (Rosqvist, 2003). The importance of such quality control procedures has been raised in an editorial of the first edition of the Risk Analysis journal, finding however that these are not well developed (Cumming, 1981).

The relation between validity and the evaluation process warrants a comment. Validity only concerns the question to what extent the measurement appropriately describes the concept one intends to describe. The evaluation of a risk analysis goes beyond this, with a focus on methodological characteristics of the risk analysis as a measurement procedure. Thus, validity is only one aspect of evaluation.

### 2.2.2 Challenges to reliability, validity and evaluation

Reliability is challenging to assess because risk analyses have unique results in the sense that these are usually not repeated for the same problem, such that little empirical evidence exists concerning measurement reliability. In the analogy of Figure 2, this means that only one measurement point is made.

[4] Different terminology is used: quality control / quality assurance / qualification (Apostolakis et al., 1983; Rosqvist and Tuominen, 2004; Suokas and Rouhiainen, 1989), verification (Graham, 1995), credibility assessment (Busby and Hughes, 2006) and validation (Rosqvist, 2010)

Validity is a challenging issue because there are different views on the risk concept (Aven, 2012b; Kaplan, 1997; Kermisch, 2012; Slovic, 1999), and hence on what a risk analysis should measure. This inevitably leads to different views on whether a given measurement is valid. In the analogy of Figure 2, this means that there is disagreement on where the bulls-eye is located[5].

Evaluating risk analyses is challenging due to diverging views on the appropriate scientific foundations for Risk Analysis, as outlined in Section 2.1 . Adherence to a realist, constructivist or proceduralist approach has repercussions on the methodological characteristics to which the risk analysis as a measurement procedure should comply. This is further addressed in Section 6.

Another essential difficulty in determining the quality of a risk analysis is the impossibility of a comparison with experiments or data. If, as understood in this thesis, risk refers to future occurrences, this is a genuinely metaphysical problem. Empirical measurements of future (non-)occurrences are impossible to make: "the most powerful method of science – experimental observation – is inapplicable to the estimation of overall risk" (Weinberg, 1981, p. 5).

Finally, many different tools and modelling approaches are used for measuring risk. This complicates the evaluation of specific risk analyses. While some general issues can be stated, the procedures to evaluate a specific risk analysis are likely to differ for different specific measurement tools (Rosqvist, 2003).

### 2.2.3 Previous research on reliability, validity and evaluation

Despite the centrality of reliability, validity and evaluation in any measurement procedure, there has been very limited research dedicated to these issues in Risk Analysis, as found by e.g. Rae et al. (2014).

Suokas (1985) evaluates the reliability and validity of two methods for assessing the risk of an industrial plant and two machinery installations. Suokas and Kakko (1989) report on reliability exercises in the nuclear industry, showing that the reported estimates for accident frequency typically vary within several orders of magnitude. Amendola et al. (1992) report on reliability studies of chemical risk analysis, concluding that variations of multiple (up to six) orders of magnitude occur for risk estimates of the same top event. Laheij et al. (2003) perform a benchmark reliability study of five methods for chemical risk analysis, finding discrepancies of about one order of magnitude.

Aven and Heide (2009) provide a theoretical discussion on the reliability and validity of risk analysis. They propose a number of reliability and validity criteria, which are applied to evaluate different approaches for quantifying risk, namely traditional statistical analysis, the 'probability of frequency' approach (Kaplan, 1997) and the 'predictive Bayesian' approach (Apeland et al., 2002).

[5] For example, if risk is understood as a combination of uncertainties, events and consequences (Aven and Renn, 2009), measurement validity involves an argumentation that the focus is on the right events and consequences, and that the associated uncertainties are appropriately assessed. If a polythetic understanding of risk is adopted (Kermisch, 2012; Slovic, 1999), measurement validity involves an argumentation that the facets considered in the measurement (e.g. probabilities, events, emotional reactions, etc.) are the appropriate ones for the specific problem, and that these are adequately measured.

The different approaches have different validity criteria, which relates to the different underlying commitments to the risk concept.

While some research on the reliability of Risk Analysis has been performed in industrial applications as indicated above, no systematic work is known in the maritime transportation application area.

Concerning the evaluation of risk analyses, Suokas and Rouhiainen (1989) identify four possibilities to do this: i) carrying out a complete parallel analysis of the same activity, ii) carrying out a parallel analysis on some parts of the same activity, iii) comparing the analysis with descriptions of accidents in the corresponding system and with personal experience, and iv) examining the process behind the analysis. Rouhiainen (1992) presents a checklist approach for evaluating risk analyses in an industrial system. Macgill et al. (2000) propose another checklist approach for the water treatment industry, which follows a two-level hierarchy. The top level contains five characteristics: observation, method, output, peer review and validity. These are further divided in sub-characteristics, which are assessed using an ordinal scale.

Rosqvist (2003) proposes four methodological quality characteristics for FSA: transparency, completeness, credibility and fairness. Completeness is assessed by inspecting the model scope in relation to the scope of the study. Credibility is assessed through three criteria: i) sensitivity analyses for dealing with parameter uncertainty, ii) model uncertainty and direction of bias and iii) adequacy of the recommendations in light of risk results and decision rules.

Busby and Hughes (2006) perform interviews to identify which norms a risk analysis should conform to, concerning both the object system to which it is applied, as well as the social system it intends to serve. A broad set of norms is identified by regulators, consultants and researchers.

Rosqvist (2010) finds that a key element in the evaluation of a risk analysis is the different roles of the experts, risk analysts and decision makers. The domain expert focuses on the availability of knowledge, the risk analyst on the appropriateness of data, experts and methods, and the decision maker on the relevance of the inferences in light of the adopted decision criteria.

## 2.3 State of the art in maritime transportation Risk Analysis

### 2.3.1 Research on Risk Analysis in maritime application area

Most of the work concerning principles and methods for maritime Risk Analysis addresses the Formal Safety Assessment (FSA) method, adopted by the International Maritime Organization (IMO, 2002). Several reviews and commentaries have been made, often critically discussing some of its deficiencies and sometimes proposing methods and ways of improving the process. Work by Wang (2006, 2002, 2001), Guedes Soares and Teixeira (2001), Skjong and Wentworth (2001), Devanney (2008), Kontovas and Psaraftis (2009), Pedersen (2010), Psaraftis (2012) and Yang et al. (2013) belongs to this category.

Wang et al. (2004) focus on the possibility of using advanced mathematical tools such as approximate reasoning, artificial neural networks and optimization in maritime risk analyses. Rosqvist and Tuominen (2004) and Busby and Hughes (2006) address the issue of the credibility of FSA studies. Montewka et al. (2014b) propose a risk perspective for FSA, which highlights the knowledge and understanding about the system behaviour.

Several authors focus on risk acceptance or cost effectiveness criteria for use in risk cost benefit analyses in maritime applications. These either provide a general overview of risk acceptance and cost-effectiveness principles (Skjong et al., 2007; Trbojevic, 2006; Vanem, 2012), propose new criteria (Puisa and Vassalos, 2012), discuss the extension to environmental risk (Psaraftis, 2008) or perform analyses to propose numerical values for the decision criteria (Eide et al., 2009; Kontovas et al., 2010; Psarros et al., 2011; Yamada, 2009).

Despite the significant number of papers written about FSA-related issues, there is no research known which specifically focuses on the underlying scientific methods for Risk Analysis in the maritime application area, which is the topic of PI.

### 2.3.2 Waterway risk analysis applications

Many methods and applications of waterway risk analysis have been presented. Review papers by Li et al. (2012) and Özbaş (2013) outline the rationale of some of the most influential models, in particular traffic flow, traffic simulation, and event tree models. Mazaheri et al. (2014) review available models addressing the risk of ship grounding from a risk management perspective.

Various models have been proposed for waterway risk analysis, based on traffic flow theory (Fowler and Sorgård, 2000; Mulyadi et al., 2014; Pedersen, 1995), traffic simulation (Almaz, 2012; Merrick et al., 2000; Sormunen et al., 2014; Ulusçu et al., 2009), ordinal logistic regression and a vessel conflict technique (Debnath, 2009), Bayesian Networks (Hänninen et al., 2014; Klemola et al., 2009; Montewka et al., 2014a), risk indicators (Qu et al., 2011), fuzzy logic (Hu et al., 2007; Wang et al., 2014) and artificial force fields (Montewka et al., 2011; Xiao, 2014).

While many different models are developed, no research is known concerning the underlying principles adhered to in maritime risk analysis applications. This is the primary research objective of PI. In PIII, a framework for maritime transportation risk analysis is developed in which the risk-theoretical basis is elaborated upon, and an application of oil spill risk analysis in a waterway is presented.

### 2.3.3 Risk analysis applications in a ship collision avoidance context

In a ship collision avoidance context, there are two main classes of risk analysis applications.

A first class concerns methods for automatic collision avoidance and route planning. Various methods have been proposed for this purpose, see Staheros et al. (2008), Tam et al. (2009) and Campbell et al. (2012) for reviews. These methods rely on optimization and path planning algorithms for automatizing the collision avoidance actions of ships. Among the recent approaches, Tsou and Hsueh (2010) apply ant colony algorithms, Szlapczynski (2011) proposes evolutionary sets and Xu et al. (2014) apply multi-objective optimization.

A second class concerns methods for collision alert systems. Such risk analysis applications have a more restricted aim of only providing alerts to ship navigators and/or personnel in Vessel Traffic Service (VTS) centres, without proposing routing alternatives or automated collision avoidance actions. Hilgert and Baldauf (1997) propose heuristic criteria to categorize collision risk, refined by Baldauf et al. (2011) with fast-time simulation techniques. Kao et al. (2007) and Wang (2010) propose fuzzy ship domains. Other approaches include fuzzy expert systems (Bukhari et al., 2013; Lee and Rhee, 2001; Ren et al., 2011), domain theory and fast-time simulation (Zhang et al., 2012), Dempster-Shafer evidence theory (Li and Pang, 2013) and neural networks (Simsir et al., 2014). It is this class of applications which are addressed in this thesis.

While many different collision alert models have been presented, there is lack of research focusing on the risk-theoretical basis of such applications. Furthermore, no theoretical frameworks have been developed for operationalizing of the construct “ship-ship collision risk”. PIV addresses these issues while presenting a model for a risk-informed collision alert system.

### 2.3.4 Research on risk analysis evaluation in maritime application area

In the maritime application area, research on evaluative peer review is limited, and often framed in an FSA-context.

NRC (1998) presents an evaluation methodology for a waterway risk analysis study, focusing on the adequacy of data and methodologies, the transparency and limitations of the analysis and the consistency between the analysis and the provided recommendations. Rosqvist and Tuominen (2004) propose four methodological quality characteristics: transparency, completeness, credibility and fairness. In the risk analysis phase, the completeness is assessed by inspecting the model scope in relation to the scope of the study. Credibility is assessed through three criteria. First, sensitivity analyses dealing with parameter uncertainty are reviewed. Second, the model uncertainty and direction of bias is considered. Third, the adequacy of the recommendations in light of the risk results and the decision rules is assessed. Busby and Hughes (2006) perform interviews to identify which norms a risk analysis should conform to. A broad set of norms is identified by regulators, consultants and researchers, and a framework is outlined on how these could be integrated. Psaraftis (2012) proposes review criteria of FSA studies, including adherence to procedure and expertise of the FSA team, adequacy of data, assumptions and scope, transparency, the assessment of sensitivity and uncertainty.

Given the importance of establishing quality control mechanisms in scientific research and the limited work focusing on risk analysis evaluation, this is more elaborately addressed in PIII and PIV. Based on these, an integrated framework for model-based risk analysis is presented in Section 6.

# 3. Analysing Risk Analysis: the need for clarifying principles

This chapter addresses Objective 1 and Objective 2 of Section 1.2. Section 3.1 focuses on some foundations of waterway risk analysis applications. In Section 3.2, the reliability of risk analyses is investigated, based on case studies from waterway risk analysis and risk models in a collision avoidance context. Subsequently, research questions are defined in Section 3.3.

The **main novelties** in this chapter are:

- the analysis of waterway risk analysis applications in light of foundational issues provides new insights in the commitments to Risk Analysis made in this research community [PI];
- the classification of scientific approaches to Risk Analysis (Figure 3) is a new way to communicate the principles one adheres to [PI];
- the systematic research on reliability is unprecedented in the maritime transportation application area [PII, PIV].

## 3.1 An analysis of foundational issues through applications

In PI, the state of the art in waterway risk analysis applications is analysed in light of a number of foundational issues. The main purpose of this research is to identify how this research community has approached Risk Analysis and to support calls for intensified focus on foundations of Risk Analysis. The analysis focuses on three issues: definitions, perspectives and scientific approaches. Risk definitions provide insight in how the authors understand the risk concept. Risk perspectives encompass which elements are considered in the risk description, i.e. into which measurement tools are applied, whether only events or events and consequences are considered, and whether the risk description contains elements to convey the confidence in the analysis. The scientific approach concerns the adherence to realist, constructivist or proceduralist foundations, providing insight in whether the focus is on a true risk, the types of considered evidence, the extent of uncertainty treatment, the involvement of stakeholders and the inclusion of contextual attributes.

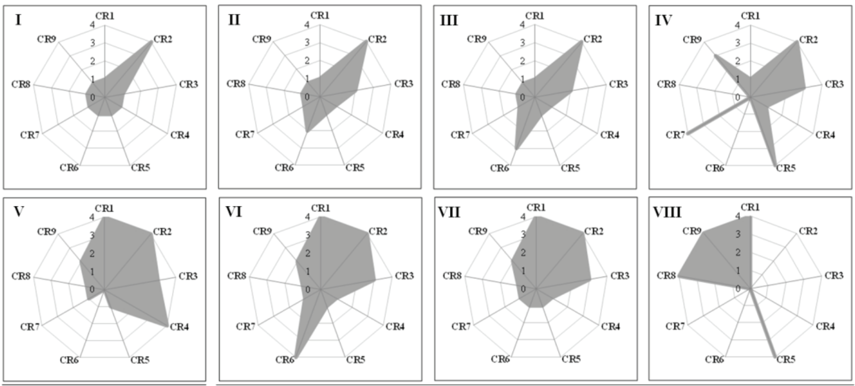
Risk definitions are classified using a categorisation proposed by Aven (2012b), see Table 2. The scientific approaches are classified in eight classes shown in Figure 3, refining the prototypical realist, constructivist and proceduralist approaches. These are more elaborately addressed in PI.

**Table 2.** A classification of risk definitions (Aven, 2012b)

| Risk definition classes | | Abbreviation |
|---|---|---|
| **D1** | Risk = Expected value | R = EV |
| **D2** | Risk = Probability of an (undesirable) event | R = P |
| **D3** | Risk = Objective uncertainty | R = OU |
| **D4** | Risk = Uncertainty | R = U |
| **D5** | Risk = Potential/possibility of a loss | R = PO |
| **D6** | Risk = Probability and scenarios / (severity of) consequences | R = P&C |
| **D7** | Risk = Event or consequence | R = C |
| **D8** | Risk = Consequences/damage/severity + uncertainty | R = C&U |
| **D9** | Risk = Effect of uncertainty on objectives | R = ISO |

The main conclusions of PI are as follows.

First, it is found that many different risk definitions are used in the application area. Risk is often not explicitly defined, and when provided, it is usually adopted as if no alternatives exist. Probability-based definitions, especially D1 (R=EV) and D6 (R=P&C) are dominant. Definitions based on possibility D5 (R=PO) and uncertainty D8 (R=C&U) are found as well, albeit minimally. This confirms research that the Risk Analysis discipline faces challenges related to the applied terminology (Aven and Zio, 2014; Kaplan, 1997).




| | |
|---|---|
| I | Strong realist |
| II | Moderate realist |
| III | Moderate realist with uncertainty quantification |
| IV | Scientific proceduralist |
| V | Precautionary constructivist |
| VI | Moderate constructivist with uncertainty evaluation |
| VII | Moderate constructivist |
| VIII | Strong constructivist |

**Note:**
0 indicates that different alternatives exist within the scientific approach

| | | | |
|---|---|---|---|
| **CR1** | **Focus on underlying true risk** | 1 | Yes |
| | | 4 | No |
| **CR2** | **Data and engineering / scientific models** | 1 | Not used |
| | | 4 | Used |
| **CR3** | **Expert judgment** | 1 | Not used |
| | | 2 | Used, but minimally |
| | | 3 | Used |
| **CR4** | **Non-epistemic values** | 1 | Not included |
| | | 4 | Included |
| **CR5** | **Lay person's judgment** | 1 | Not used |
| | | 4 | Used |
| **CR6** | **Uncertainty assessment** | 1 | Not assessed |
| | | 2 | Sporadically mentioned |
| | | 3 | Quantitative, model-based |
| | | 4 | Qualitative, beyond model |
| **CR7** | **Stakeholder involvement** | 1 | Not involved |
| | | 4 | Involved |
| **CR8** | **Contextual attributes** | 1 | Not considered |
| | | 4 | Considered |
| **CR9** | **Link to decision making** | 1 | Decision criteria, risk-based |
| | | 2 | Managerial review and judgment |
| | | 3 | Stakeholder process |
| | | 4 | No direct link |

**Figure 3.** Spectrum of scientific approaches to Risk Analysis

Second, as clear from Figure 4, definitions do not necessarily provide insight into the scientific approach to Risk Analysis. This justifies earlier claims that underlying risk definitions, deeper philosophical disputes exist regarding the nature of the risk concept and the appropriate principles underlying analyses:

> The claim that there are competing conceptions of risk implies that [...] competing interpretations reflect philosophical differences that are long-standing and systematically linked. Such disputes will not be settled merely by stipulating

> definitions for the disputed terms. Generally speaking, stipulative definitions for risk will be useful only when the discourse community [...] already possesses a shared conception of risk (Thompson and Dean, 1996, p. 363).

Third, it is found that there is a significant relation between the applied definition and the adopted risk perspective, see Table 3. For definitions based on probability (D1, D2 and D6), risk descriptions typically apply probabilities to describe risk. In such cases, uncertainties beyond the probabilities are typically not assessed. In contrast, the application where risk is defined through uncertainty (D8) also applies probabilities to measure risk, but a systematic uncertainty evaluation accompanies the risk description. Furthermore, in applications where risk is defined through possibility (D5) or as an event (D7), more risk descriptions use indicators and fuzzy numbers. This means that a commitment to a certain definition to a large degree determines how one describes it, as asserted e.g. by Slovic (1999).

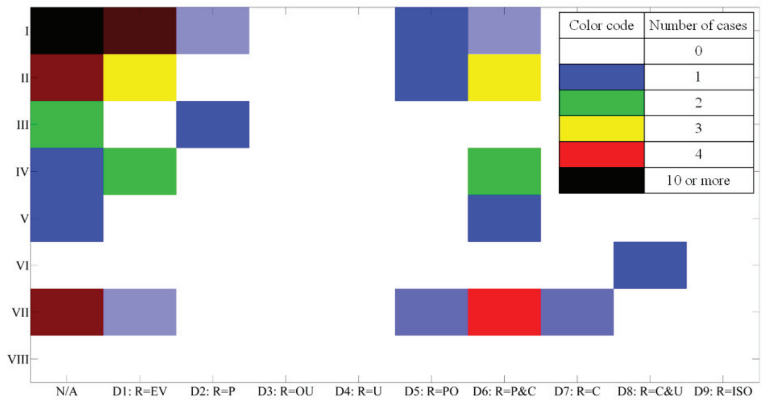



**Figure 4.** Relation between risk definitions (Table 2) and scientific approaches to Risk Analysis (Figure 3) in maritime waterway risk analysis applications analysed in PI

**Table 3.** Relation between risk definition and risk perspective, abridged from PI

| Risk definition | ID | $P_f^*$ | $P_s$ | $P_x$ | $I_{QU}$ | $I_{QL}$ | F | A | C | $C^*$ | $U_{QU}$ | $U_{QL}$ | $U_{AH}$ | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1: R=EV | M6 | x | | x | | | | x | | x | | [x] | | |
| | M11 | x | | | | | | x | x | | | | | |
| | M18 | x | | | | | | x | x | | | | | |
| | M25 | x | x | | | | | x | x | | | | | |
| | M48 | x | | | | | | x | x | | | | | |
| D2: R=P | M34 | x | | | | | | x | x | | | | | |
| | M54 | x | x | x | | | | x | x | | | | | |
| D5: R=PO | M17 | | | | | | x | x | x | | | | | |
| | M43 | x | | | | x | | x | x | | | | | |
| D6: R=P&C | M9 | x | | x | | | | x | x | | | | | |
| | M12 | x | | x | | | | x | x | | | | | |
| | M26 | x | x | | | | | x | x | | | | | |
| | M37 | x | x | | | | | x | x | | | | | |
| | M51 | x | x | | x | x | | x | x | | | | | |
| D7: R=C | M17 | | | | | | x | x | x | | | | | |
| | M43 | x | | | | x | | x | x | | | | | |
| D8: R=C&U | M56 | x | x | x | | | | x | x | | | x | | |

ID = identification number, $P_f^*$ = frequentist probability, $P_s$ = subjective probability, $P_x$ = modelled probability, $I_{QU}$ = quantitative indicator, $I_{QL}$ = qualitative indicator, F = fuzzy number, A = event, C = consequence, $C^*$ = consequence [should be, but is not, included], $U_{QU}$ = quantitative measure of evidential uncertainty, $U_{QL}$ = qualitative measure of evidential uncertainty / strength of knowledge, $U_{AH}$ = alternative hypothesis-based epistemic uncertainty, B = bias, x = found in risk description, [x] = mentioned, not systematically analysed

Fourth, it is found that within the waterway risk analysis application area , a wide spectrum of scientific approaches to Risk Analysis co-exists. Most applications adhere to a form of the realist prototype (I-III). Constructivist approaches (V-VII) are found as well, but less frequently. The proceduralist approach (IV) constitutes a minority in the application area.

Finally, the lack of systematic uncertainty treatment in most applications is apparent. Of the 58 investigated applications, only six considered uncertainty: three provided a quantitative uncertainty analysis (addressing model parameters or structure), while in three cases, the risk model is accompanied with a qualitative description of uncertainties or biases. This lack of uncertainty treatment contrasts the findings in the example applications of PI from p. 128 onwards, where several important uncertainties can be identified.

The above findings support calls for intensified research and discussion on the appropriate underlying principles of maritime risk analysis applications.

## 3.2 Analysing reliability: two case studies

In PII, the reliability of selected waterway risk analysis applications is investigated. In PIV, the inter-methodological reliability of four risk models for a ship collision alert system is assessed. The main purpose of this research is to provide some evidence to the claims in the theoretical analysis by Aven and Heide (2009) that risk analyses are generally not reliable tools for informing decisions. These authors propose following reliability criteria:

R1. Degree to which a risk analysis method produces the same results at reruns of the method.

R2. Degree to which a risk analysis produces identical results when conducted by different analysis teams, using the same methods and data.

R3. Degree to which risk analyses produce identical results when conducted by different analysis teams with the same scope and objective, but no restrictions on method and data.

In PII, three waterway risk analyses methods are applied to a case study in the Gulf of Finland (GoF). The analysis focuses on the question how likely ship-ship collisions are in different locations in the sea area. The methods determine the likeliness of collision using probabilities or using quantitative indicators, see Table 4. In methods M2 and M3, which apply probabilities to measure risk, the accuracy of the calculated numbers can be assessed. However, comparisons between the calculated probabilities (M2 and M3) and the quantitative indicators (M1) can only be performed by inspecting the rank order of the risk measures in the waterway areas.

**Table 4.** Summary of perspectives and scientific approaches, methods applied in PII

| ID | Reference | Risk perspective | Scientific approach to Risk Analysis |
|---|---|---|---|
| M1 | Qu et al., 2011 | $R \sim (I_{QU} \rightarrow A)$ | II – moderate realist |
| M2 | Weng et al., 2012 | $R \sim (P_f^*, A, C^*)$ | I – strong realist |
| M3 | Goerlandt and Kujala, 2011 | $R \sim (P_f^*, A, C^*)$ | I – strong realist |

Abbreviations of risk perspectives, see Table 3. Rationale of scientific approaches, see Figure 3.

In Figure 5, the results of the R3-reliability criterion for these methods are shown, by means of pairwise comparisons of the risk measures as determined by the three methods in 16 defined areas of the investigated TSS area[6].

The diagonal provides information about the considered test cases R3.i to R3.vi. Below the diagonal, each matrix element shows a comparison between the calculated risk measures for the corresponding test case. Above the diagonal, three correlation coefficients for the risk measures are shown: Spearman rank ρ, Kendall's τ and (if meaningful) Pearson's r. These provide a mathematical appreciation of the strength of the relation between the metrics[7].

Figure 5 clearly shows that the inter-methodological reliability of the risk analyses is low. For instance, comparing R3.iii (M2) with R3.v (M3) results in ρ = 0.47 and τ = 0.32. This means that the rank order of the risk measures in the different waterway areas is poorly retained across the methods.

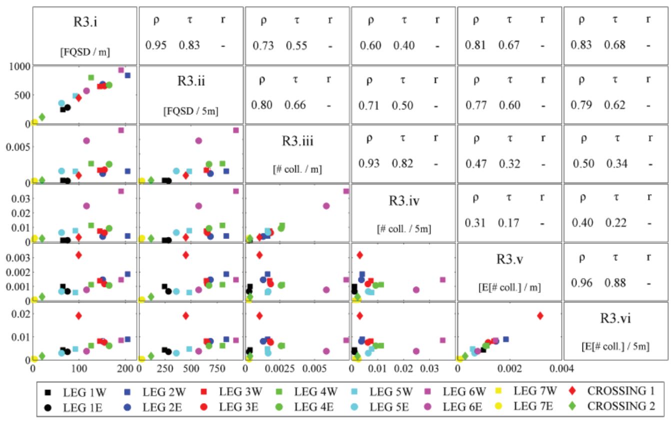



**Figure 5.** Inter-methodological (R3)-reliability of selected models for waterway risk analysis, test cases (shown on the diagonal, together with the axis labels) from PII

Table 5 summarizes the results for the methods of Table 4. For the deterministic methods M1 and M3, R1-reliability is fulfilled. For the probabilistic method M2, R1-reliability is high. R2-reliability of the methods depends on the parameter choices within each method: reliability in terms of accuracy and rank order vary from low to high. R3-reliability is low.

**Table 5.** Summary results of the reliability scores for risk analyses investigated in PII

| Method | Reliability criterion | Accuracy of metric | Rank order retention |
|---|---|---|---|
| M1 | R1 | N/A | Y |
| | R2 | N/A | L-H |
| | R3 | N/A | L |
| M2 | R1 | H | H |
| | R2 | M-H | M-H |
| | R3 | L | L |
| M3 | R1 | Y | Y |
| | R2 | L-M | L-H |
| | R3 | L | L |

R1, R2, R3 = criteria by Aven and Heide (2009), N/A = not applicable, Y | L | M | H = yes, low, medium, high

[6] TSS: an area where ship traffic is regulated, requiring vessels to follow certain sea lanes.

[7] In PII, particularly on p. 356, it is elaborated how to read the figure.

In PIV, five risk models for collision alert systems are compared as part of an evaluation of the proposed risk model. Figure 6 shows the time histories of the four test scenarios for these methods, shown as videos in PIV. The sequences show the low inter-methodological (R3) reliability for the considered methods, for all considered scenarios.

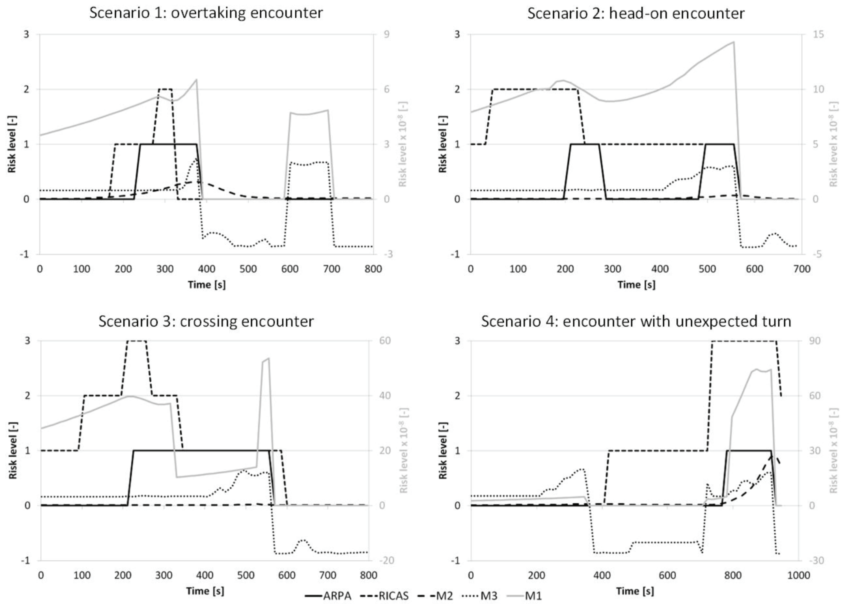



**Figure 6.** R3-reliability of selected models for risk-informed collision alert systems, test scenarios from PIV. ARPA = industry standard, e.g. Baldauf et al. (2011). RICAS = PIV. M1 = Mou et al. (2010). M2 = Wang (2010). M3 = Bukhari et al. (2013)

The analyses performed in PII and PIV confirm the theoretical discussions by Aven and Heide (2009), providing some empirical evidence about the reliability of risk analysis in the maritime transportation area. Compared with Aven and Heide (2009), who focus on probability-based risk perspectives, it is shown that also perspectives applying indicators ($I_{QU}$ or $I_{QL}$) or fuzzy numbers (F) do not lead to a reliable risk characterization.

## 3.3 Research questions

Based on the findings of Section 3.1 and 3.2, the following research questions are formulated, which are addressed in the following Sections:

1. Given the conceptual/terminological disarray in the application area, what is a coherent terminological basis for maritime transportation risk analysis?
2. If risk models and analyses are unreliable, how can these be used?
3. How do the above principles translate to practical frameworks?
4. How can we establish credibility of a risk model/analysis, i.e. how can risk analyses be evaluated?

# 4. Risk and model-based risk analysis: principles

This chapter focuses on Objective 3 as identified in Section 1.2, with corresponding research questions 1. and 2. of Section 3.3. The **main novelties** are:

- the definitions of risk and related concepts constitute a novel, coherent set of principles to approach Risk Analysis [PIII, PIV][8];
- the discussion on the relation between risk modelling and prediction, from which the proposed model uses are established [PIII, PIV][9].

## 4.1 Terminological-conceptual basis

When terminologies are disputed, definitions are important. In this section, the adopted definitions and understanding of the concepts in the frameworks for risk analysis, presented in PIII and PIV, are introduced. The underlying rationale and some implications are outlined as well, which is instructive because there are different views on definition as an intellectual activity[10] and because different types of definitions have a different aim[11].

### 4.1.1 On the logic of definitions

A definition is the result of an intellectual activity for setting out the meaning of symbols or words (Moore, 2009). The definiendum is the symbol being defined, whereas the definiens is the (group of) symbol(s) explaining the mean-

[8] It is acknowledged that the various definitions exist in some form through work of previous authors, as referenced. The novelty is modest in the sense of integrating various ideas into a coherent set (e.g. the relation between risk and situations, the relation between risk and different types of uncertainty and the distinction between uncertainty, acceptance and bias). The aim is to propose a coherent web of related terms and to clarify how these can be understood. While briefly presented in PIII and PIV, the discussion in Section 4.1 and 4.2 is more elaborate than in these papers. The discussion in Section 4.1.3 is not given in the papers.

[9] The issue of the non-predictive nature of the risk models is briefly presented in PIII and PIV, but is elaborated upon in Section 4.2.

[10] There are essentialist, linguistic and nominalist views on definition. Generally, essentialists maintain that definitions (should) provide a causal explanation of the thing defined; linguists view definitions as historical reports of word usage; and nominalists see definitions as syntactic or semantic rules for assigning names to things. (Moore, 2009)

[11] Moore (2009) mentions three aims: lexical (historically reporting of the actual usage of a term), stipulative (deliberately assigning a meaning to an old term in a new way) and precising (stipulating additional features to an established usage of the word, for adding precision).

ing of the definiendum. In the cases of Table 2, the method of definition is analytical[12] and intensional[13]: the phenomenon referred to by the term is broken down into its constituent elements, which are the attributes or characteristics shared by the class to which the term is applied.

Swartz (1997a) outlines the two main tenets of the Classical Theory of Definition: i) a 'proper' intensional definition states in the definiens the logically necessary and sufficient conditions for applying the definiendum, and ii) there are intensional definitions for each term we use. These tenets are controversial, and it has been argued that there are many phenomena for which there are no necessary conditions common to all members of the class[14]. Rather than an absolute set of necessary conditions, there is “a complicated network of similarities overlapping and criss-crossing: sometimes overall similarities, sometimes similarities in detail” (Wittgenstein, 1953, pp. §66, p.27e). The implication of this argument is that there are terms for which it is impossible to construct a precise intensional definition (Moore, 2009), which is compatible with Hansson’s (2000) argument that it is a myth to seek a single, all-compassing risk definition and with the view that, sometimes, “a concept with blurred edges” is exactly what we need (Wittgenstein, 1953, pp. §71, p.29e).

Considering the above, risk is in this thesis understood as a polythetic concept. Thus, while there are general features of the concept which allow one to parse and interpret when the risk concept applies, there is no unique set of necessary conditions. Hence, which features are in focus depends on the application context and is a choice requiring justification.

Definitions for and the adopted understanding of key concepts are provided in the next section. While these may contribute to clarifying terminology in Risk Analysis (one of the main research issues identified by Aven and Zio (2014)), these should not be construed to resolve the ongoing debates over the essence of these concepts. We concur with the view of Moore (2009):

> [...] we will limit our ambitions to fashioning precising definitions [...] while drawing upon the many and varied meanings that previous thinkers have ascribed to these terms, we will attempt to be *precise* or *particularize* [original emphasis] their meanings within the bounded context of the conceptual framework of which they will be integral parts. What is important here is not that we succeed in contriving definitions upon which everyone in the scholary community can agree (an impossible task). Rather, what is essential is that we be clear *in our own minds* [original emphasis] – and make clear to those to whom we will communicate the fruits of our labours – what we mean [...].

[12] In analytical definition, the defeniens sets out the individually necessary and jointly sufficient conditions for the correct application of the definiendum. Other methods exist, e.g. denotative (citing examples of the object class) and synonymous (providing another word with the same general sense as the definiendum) (Swartz, 1997).

[13] Versus extensional, which lists examples of objects belonging to the class (Swartz, 1997)

[14] Wittgenstein (1953) uses the “game” concept as illustration, referring to card games, board games, ball-games, Olympic games, etc. Finding no necessary conditions common to all these activities, he speaks of “family resemblances”. An activity having sufficient of these similarities can justifiably be taken as a “family member”. See also Slovic (1999) and Kermisch (2012).

### 4.1.2 Definition of risk, related concepts and measurement tools

Definitions and a brief outline of the adopted understanding of the key concepts underlying the frameworks of PIII and PIV are summarized in Table 6. Selected characteristics of the concepts as understood in this thesis are listed, allowing further insight in how these are understood. Definitions of key measurement tools applied in the frameworks are summarized in Table 7.

**Table 6.** Concepts, definitions and brief outline of adopted understanding[15]

| Definiendum | Definiens<br>Further outline of the adopted understanding<br>Reference(s) |
|---|---|
| Acceptance | A cognitive attitude in which an assessor presupposes a premise for specific reasons in the deliberation<br>• Under voluntary control of assessor, action-oriented rather than truth-oriented<br>• Varies with context, can be based on non-epistemic values<br>Elliott and Willmes (2014) |
| Belief | A cognitive attitude in which an assessor considers a premise true<br>• Is not under voluntary control of assessor, truth-oriented<br>• Is independent of context, not based on non-epistemic values<br>Elliott and Willmes (2014) |
| Bias | The qualitative difference between what one believes to be the truth and an imperfect representation of this truth which is accepted in a given context<br>• Has an epistemological-normative connotation: relates to knowledge and values<br>• Directional, in the sense that conservative (overestimating) and optimistic (underestimating) biases exist<br>Rosqvist and Tuominen (2004) and Elliott and Willmes (2014) |
| Consequence | A specific type of event which is causally connected to another event, i.e. under conditions of constant conjunction, temporal succession and spatial propinquity<br>Solberg and Njå (2012) |
| Event | A specific (defined) state of the world and how that state changes or develops over a time interval<br>Solberg and Njå (2012) |
| Likeliness | A qualitative, argumentative appreciation of how much more one believes that an event will occur, compared to other events or to its opposite non-occurrence<br>van der Helm (2006) |
| Possibility[16] (factually epistemological) | Something we can think of, which we suppose to be grounded in factual reality<br>• Has philosophical-ontological connotation: relates to what can or could exist<br>• Is of binary nature: either something is possible or not, with nothing in between<br>• Can only be described in hypothetical terms, either because the premises are not yet corroborated or because the premises are not yet known<br>van der Helm (2006) |
| Risk | A concept which refers to the possible but uncertain occurrence of a situation where something of human value is at stake<br>• A “bridge” between possible futures and a present time<br>• Used for exploring future possibilities and for coping with identified possibilities<br>• Possibility is understood in factually epistemological, uncertainty in ontic sense<br>• Refers to future situations which we believe could become a reality<br>• Depending on the context, the focus of the possible situation can be an event, or both events and consequences<br>Hansson (1999) and Solberg and Njå (2012) |
| Situation | A contextual whole consisting of a set of circumstances<br>• Has a complex structure, including focus, foreground, background and horizon.<br>• It includes objects, events, agents, their relations, the background on which all these appear, and a qualitative experienceable unity.<br>Brown (2012) |
| Uncertainty (aleatory) | The inherent variation associated with a considered physical system or environment<br>Levin (2005) |
| Uncertainty (epistemic, evidence) | The lack of knowledge about evidential elements $e_1$, … $e_n$ which stand in an evidential relation to an assessor’s statement about the possible occurrence of an outcome<br>Levin (2005) |

[15] Behind all these concepts lay complex philosophical questions. Focus is on providing clarity through distinction rather than through definition, a view shared by e.g. van der Helm (2006).

[16] This is one of the four types of possibility identified by Bloch (1995). The other three are the ‘formally possible’ (all we can think of, even if nonsensical or contradictory), the ‘possibile according to the object’ (an characteristic of an object, which entails that it can have certain implications) and the ‘objectively real possible’ (the determinism present in the object-world).

| | |
|---|---|
| Uncertainty (ontic) | A metaphysical limit to human knowledge, rooted in the relation between time and states of affairs<br>• A characteristic of the world and how it works, cannot be fully eradicated by increasing knowledge<br>• The result of the inaccessibility of the future for human considerations<br>Solberg and Njå (2012) |
| Uncertainty (epistemic, outcome) | A cognitive attitude in which an assessor simultaneously entertains different rival beliefs concerning an outcome which is indeterminate at the time of consideration<br>Levin (2005) |

**Table 7.** Measurement tools and their definitions

| **Definiendum** | **Definiens**<br>**Reference(s)** |
|---|---|
| Alternative hypothesis-based epistemic uncertainty assessment | An expression of epistemic uncertainty, particularly related to model structure, by weighing multiple plausible hypotheses related to a phenomenon<br>Zio and Apostolakis (1996) and Aven and Zio (2011) |
| Fuzzy number | The degree to which a specific instance belongs to a certain category, i.e. the degree of similarity between the instance and the category<br>Mendel (1995) and Bilgiç and Türkşen (1998) |
| Indicator | A measure of a system characteristic, used as a proxy for inferring the likeliness of occurrence of events and/or consequences<br>Davies et al. (2006) and Beasley et al. (2010) |
| Probability (Frequentist) | The fraction of time a specified outcome occurs in an in principle infinite number of repeated tests<br>Watson (1994) and Aven and Reniers (2013) |
| Probability (Subjective) | The degree of belief of an assessor based on evidence available to him/her<br>Watson (1994) and Aven and Reniers (2013) |
| Qualitative measure of evidential uncertainty or strength of knowledge | A linguistic or numerical measure on an ordinal or categorical scale indicating the degree of lack of knowledge or the strength of knowledge for making a measurement or a statement<br>Flage and Aven (2009), Kloprogge et al. (2011) and (Aven, 2013) |

### 4.1.3 Application of risk-conceptual basis in a risk analysis

The adopted use of the concepts is illustrated in Figure 7 for the framework of PIII and in Figure 8 for the framework of PIV. A clear distinction is made between the concepts and their measurement, a fundamental requirement of measurement theory (Trochim and Donnely, 2008). In the risk identification stage, the risk concept is used to explore the space of possible occurrences which are relevant to the considered decision problem. In the risk measurement stage, a statement is made about how likely (qualitative measurement) or how probable (quantitative measurement) these occurrences are. An evidence assessment moderates the measurement.

In Figure 7 (top), the risk concept is used to identify relevant events A and consequences C in a possibly occurring situation. The main situational qualities SQ, i.e. the features relevant for conceptualizing the events A and consequence C, are identified. These constitute the foreground of the situation, but prior events, further consequences and additional situational qualities (marked in gray) are conceivable as a background of the situation. The focus of the situation is the consequence C.

The situation is delineated using the available evidence (broadly construed), which is conditional to the decision context in two ways. First, the available resources (time, money, expertise,…) limit the strength of the evidence base, which indirectly affects the identified events. Second, the decision context and stakeholder values guide the risk analysis to focus on those parts of the situation which are valued in the decision making process. Thus, the risk analysis and decision context are not independent (Vareman and Persson, 2010).

In Figure 7 (bottom), the situational qualities, events and consequences are measured. This is further explained in PIII, from p. 44 onwards.

In Figure 8 (top), the risk concept is used to identify relevant events A in a possibly occurring situation. A is the focus of the situation, but prior events, further consequences and situational qualities are conceivable as a situational background. The assessor uses knowledge about the system states available to him to interpret a current situation based on its situational qualities. From this, an interpretation is made about the possible event occurrence.

In Figure 8 (bottom), the situational qualities are measured and combined to provide an indication of the possible event occurrence. This is further explained in Section 5.2 and PIV, from p. 5 onwards.

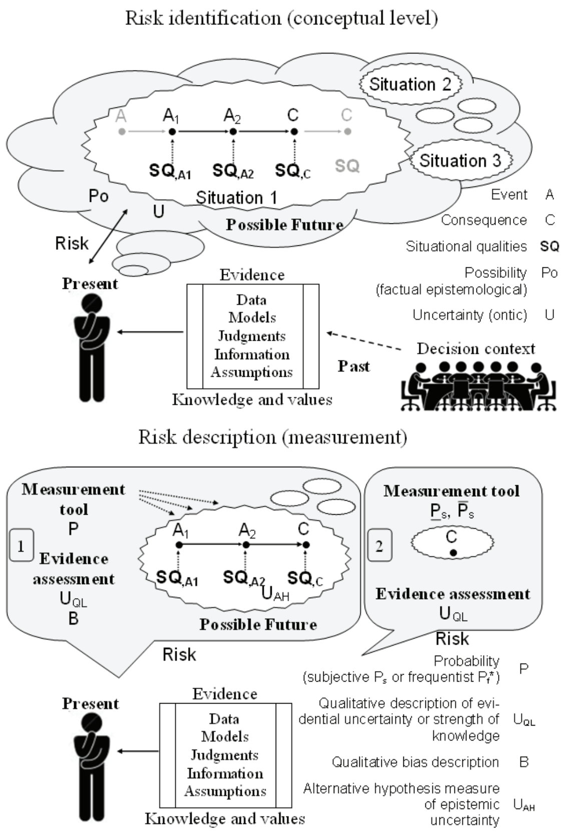



**Figure 7.** Use of concepts of Table 6 and Table 7 in risk identification and risk measurement stage, framework of PIII (policy-oriented risk analysis)

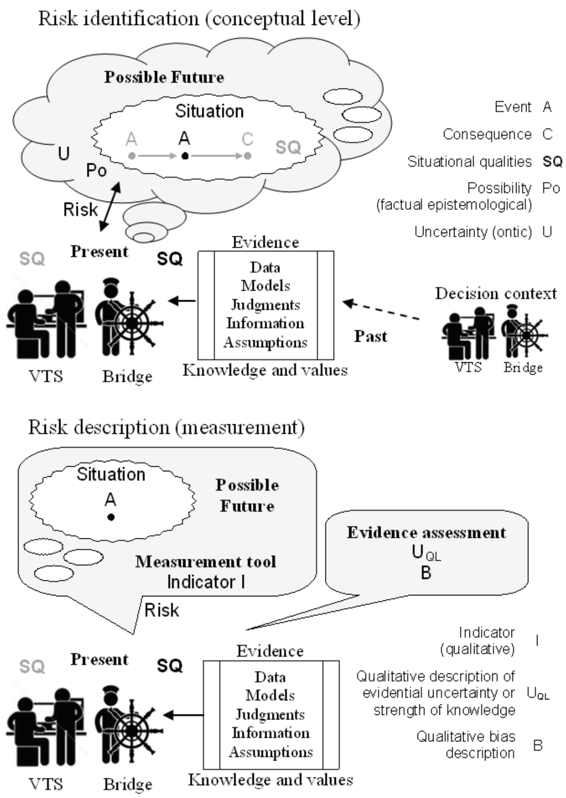



**Figure 8.** Use of concepts of Table 6 and Table 7 in risk identification and risk measurement stage, framework of PIV (operational risk analysis)

## 4.2 Risk Analysis: modelling, prediction and uncertainties/biases

PII and PIV provide evidence regarding the unreliability of risk models and analyses, confirming limited available research from other industries. Because reliability is a prerequisite for accuracy (Crawford, 2001), it seems implausible that accurate risk estimation is possible[17]. This leads to the question how risk models can justifiably be used. One central issue in this context is the relation of the model with prediction.

In Risk Analysis, it is a quite common conception that risk analyses make predictions, e.g. Apeland et al. (2002) and Rae et al. (2014)[18]. Solberg and Njå (2012) make more reservations, finding that the laws of nature can be used to make predictions, but that due to ontic uncertainty (defined in Table 6), these are not certain. Apostolakis (2014) asserts that QRA models do not predict the future, but presents no justification for this view.

In PIII and PIV, the starting premise is taken that risk models in socio-technical systems are non-predictive tools. This is considered next.

[17] This may be contrasted with the finding in PI that many waterway risk analyses focus on an accurate quantification of an underlying true risk and present the results as such.

[18] Various authors differ also on *what* is predicted: some focus on predicting observable quantities or *events* (Apeland et al., 2002, p. 94), others on predicting *risk* (Rae et al., 2014, p. 4).

### 4.2.1 Prediction: definition and criteria

Hodges and Dewar (1992) define a predictive use of a model as follows: i) a statement about an observable or potentially observable quantity or event is produced, ii) the modelled situation is such that predictive accuracy *can* be measured, and iii) the predictive accuracy of the model in the situation *has* been measured. The last two requirements significantly restrict the common usage of the word "prediction", which only accounts for the first requirement.

The restricted definition is adopted, for two reasons. First, it allows a clear distinction between different types of model uses: predictive model uses require a warrant of predictive accuracy, whereas non-predictive model uses do not. Second, the clarification regarding model use has implication for how validation is understood. For predictive models, validation consists of tests to measure the accuracy, justifying that the model *in itself* provides warranted conclusions. For non-predictive model use, validation (or better: *evaluation*) requires different standards for quality assurance (Hodges and Dewar, 1992)[19].

Hodges and Dewar (1992) list four criteria for prediction to be possible. The situation being modelled must: i) be possible to observe and measure, ii) exhibit constancy of structure in time, iii) exhibit constancy across variations in conditions not specified in the model, and iv) permit the collection of ample data to make tests concerning the model accuracy[20].

Condition iv) is violated for risk models in complex socio-technical systems such as the maritime transportation system: if risk refers to future occurrences, data collection is impossible. Moreover, models for socio-technical systems generally fail to meet the constancy-criteria ii) and iii) (Oreskes, 1998; Scher and Koomey, 2011)[21]. Hence, they cannot be used for prediction.

This instability of open systems (criteria ii) and iii)) is an underlying reason why accident modelling using linear causal relations is controversial. Several rival theories exist regarding the mechanisms by which accidents occur in complex socio-technical systems (Heinrich, 1931; Hollnagel, 1998; Leveson, 2004; Perrow, 1984; Rasmussen, 1997; Reason, 1990), see Qureshi (2007) for a summary. Several of these argue against linear cause-effect modelling, which is understandable because certain causal relations may not be stable in open systems. Where causal relations can justifiably assumed to be stable, models based on linear causation can be used to obtain insight in the system.

Linear causality models are especially controversial when models are used for accident prevention related purposes (Hänninen, 2014). One argument for this is that certain risk mitigating interventions may results in feedback within

[19] The common usage of the term "prediction" provides no way to distinguish use cases or different quality standards for different uses.

[20] Criteria i) and iv) are self-explanatory. Criterion ii) ensures that the model is predictive for the same conditions as those in the validation tests. Criterion iii) ensures that the model remains predictive for conditions differing from those in the validation tests.

[21] Taking the application of PIII, criterion ii) and iii) may be violated because different ships begin trade in a given sea area, because new regulations require new safety devices or procedures, etc. In the application of PIV, criterion ii) and iii) may be violated due to unexpected actions of one of the vessels or because other COLREG regulations induce a different situational interpretation, e.g. because a vessel is "engaged in fishing".

the system: people can adapt to the changes, possibly nullifying or reducing the intended effect (Adams, 1995). Another argument is the phenomenon known as risk migration: the introduction of a risk mitigating measure to address one problem in the system may introduce other, unexpected consequences in another part of the system (Grabowski et al., 2000).

### 4.2.2 Uses of non-predictive models

The above elaboration is made to clarify the intended use of models in the risk analysis frameworks of PIII and PIV. Risk models, if not predictive, are primarily useful heuristically. Non-predictive models are representations for providing insight and guiding further inquiry, but are not susceptible to proof (Oreskes et al., 1994). This is in agreement with the adopted understanding of the risk concept outlined in Section 4.1.2: it is used for exploring possible occurrences, not to uncover an underlying truth.

Hodges (1991) identifies a number of uses for non-predictive models, taken as a basis for the risk analysis frameworks of PIII and PIV.

In PIII, the model is intended for informing a policy decision. The model conveys an argumentation based on available evidence, provides a basis for communication between stakeholders, and serves as an aid to thinking.

In PIV, the intended model use is in an operational context. The model provides alerts to distinguish the urgency of collision avoidance actions for different vessels in the area, aimed at enhancing situation awareness and for supporting operators' judgments. It can provide a basis for communication between ship officers and VTS operators, serving as an aid to thinking.

In both frameworks, it is essential that the models do not lead to a decision in and by themselves: different mechanisms are applied for looking beyond the model. In PIII, this is an extensive evidence and assumption assessment scheme, leading to an informed judgment on risk. In PIV, information from other sources such as VHF radio, radar and ECDIS is used to judge the risk level and plan appropriate actions[22].

### 4.2.3 Accounting for uncertainty and bias

In PI, it is found that only a small minority of waterway risk analysis applications explicitly account for uncertainty. In the framework of PIII, uncertainty and bias are given important roles through an evidence assessment, alternative hypothesis and an assumption effect assessment. In PIV, evidential uncertainties and biases are assessed through a qualitative evidence assessment. Additional uncertainties, requiring further research before applying the model in operational practice, are identified as well. The need for broadly considering uncertainty and bias is discussed in PI, p. 127.

The main argumentation for considering uncertainty is provided by Douglas (2009) that scientists have a responsibility to consider the consequences of

[22] VHF: Very High Frequency, ECDIS: Electronic Chart Display and Information System

error. If evidence is poor and if this may lead to foreseeable changes to the conclusions of an inquiry, these uncertainties need to be made explicit[23].

Biases differ from uncertainty as they may carry a normative content, see Table 6. It has been argued that in applied and policy-oriented sciences, non-epistemic values can have a direct role in inferential choices.

Two arguments support this. The first is the "gap argument": if available evidence is insufficient for supporting a claim, moral or social values can be used to fill the evidential gap (Brown, 2014; Wandall, 2004)[24], by e.g. preferring conservative choices. The second goes significantly beyond this by arguing that certain models *ought* to be based on non-epistemic values. The reasoning behind this is rooted in the intended aim and use of the model (Diekmann and Peterson, 2013)[25]. This is in line with the pragmatist functionalist view on inquiry, where facts and values have different functional roles, are jointly necessary and rationally revisable (Brown, 2014)[26].

The main issue is that if values which are believed to be controversial are relied on, these should be made explicit (Hermansson, 2012; Wandall, 2004).

#### 4.2.4 Model uses in relation to uncertainties and biases

While in both frameworks the risk models have similar uses (as a platform for thinking and an aid to communication), the relation between the risk models and the uncertainties/biases in the risk analysis context differ on an important point.

In the policy-oriented risk model use (PIII), the entire model is subject to scrutiny for a subsequent judgment. In the operational risk model use (PIV), the model is used as a kind of 'black box' during operations, with only the model output informing an operator's judgment. This is due to the different time scales for decision making in policy-oriented versus operational contexts. In the former, the evidence assessment is an integral part of the risk measurement (for both risk analysis stages). In the latter, the consideration of uncertainties is a separate process, performed because of the argumentation presented in Section 4.2.3. This is also illustrated in Figure 7 and Figure 8.

Consequently, the uncertainties beyond the model are in focus during the model use in the policy-oriented framework, whereas in the operational

[23] This "error argument" is one of the primary reasons why science is not (as often thought), value-free: non-epistemic values are needed to consider the consequences of error and to identify which uncertainties are relevant to assess (Douglas, 2009; Rudner, 1953). This is also one reason why a strict separation between risk analysis and risk management is untenable (Vareman and Persson, 2010)

[24] In the traditional "gap argument", non-epistemic values have a secondary role in the space fixed by the evidence: only when evidence is insufficient, values have a role (Brown, 2014).

[25] This is argued as follows: : i) models ought to be developed with one or several goals in mind, ii) sometimes one of these goals ought to be a non-epistemic goal, iii) the extent to which a non-epistemic goal is accurately reflected in a model depends on the influence of non-epistemic values. Hence, some models ought to be influenced by non-epistemic values.

[26] There is ongoing debate on the appropriate roles for values in science and Risk Analysis, see e.g. Douglas (2009), Brown (2014) and Aven and Zio (2014). The view adopted in this thesis is in line with the analyses provided in Diekmann and Peterson (2013) and Brown (2014).

framework, uncertainties need to be addressed and as much as possible eliminated during model development.

In both cases, the biases need to be in line with stakeholder values. In the policy-oriented risk model, conservative choices are preferred because a precautionary decision maker is assumed. In the operational risk model, different values need to be considered. Conservative model choices are preferred as raising the alarm earlier rather than later is considered beneficial from an accident prevention viewpoint. However, a balance needs to be sought such that the number of alerts raised in practice is kept sufficiently low. This last point is also a user value: it is good not to be "disturbed" by alarms too frequently.

## 4.3 Implications of the adopted principles to Risk Analysis

In light of the scientific approaches to Risk Analysis outlined in Section 2.1 and 3.1 (Figure 3), the frameworks of PIII and PIV can be understood as primarily "precautionary constructivist with uncertainty evaluation".

Understanding risk as somebody's interpretation concerning possible but uncertain future situations, it is constructivist: risk does not exist independently from the people assessing and experiencing it. A wide evidence base is allowed: data, models, judgments, assumptions and non-epistemic values.

The precautionary nature of the approach is clear in PIII by making the value-laden biases underlying the risk model construction explicit. In PIV, the value-ladenness is inherent in the model due to certain conservative parameter choices. Uncertainties are broadly assessed beyond the model. In PIII, these are an integral part of the process of informing the decision. In PIV, these are used to indicate which parts of the model would benefit most from additional evidence-seeking efforts, and for identifying additional questions which would benefit from research efforts before implementing the model in practice.

In both frameworks, the focus is not on the produced numbers per se. While the numbers translate available evidence in numerical form to allow further mathematical inferences, the model-based results should be seen in a wider knowledge-seeking effort. The models suggest a certain risk level, but it is an assessor or a group of assessors who deliberate on the model outcome to form a judgment about the risk, upon which is acted.

In this sense, the scientific approach may also have a procedural element as outlined in Section 2.1 and 3.1 (Figure 3), as it is possible to include different stakeholder groups in the process of deliberative judgment.

# 5. Frameworks for risk analysis

This chapter focuses on Objective 4 as identified in Section 1.2, with corresponding research question 3. of Section 3.3. The **main novelties** are:

- a 2-stage maritime transportation risk analysis framework [PIII][27];
- tools for evaluating the strength of evidence and for assessing the effect of assumptions [PIII][28];
- a 2-stage framework for collision alert systems [PIV];
- a framework for operationalizing "ship-ship collision risk" [PIV];
- the risk models in the example applications [PIII, PIV].

## 5.1 Policy-oriented risk analysis: accidental risk in a waterway

### 5.1.1 Framework

Understanding risk as in Section 4, the proposed framework consists of two stages, see Figure 9. The first is oriented towards expert-review, the second towards decision makers. It is discussed in detail in PIII, from p. 43 onwards.

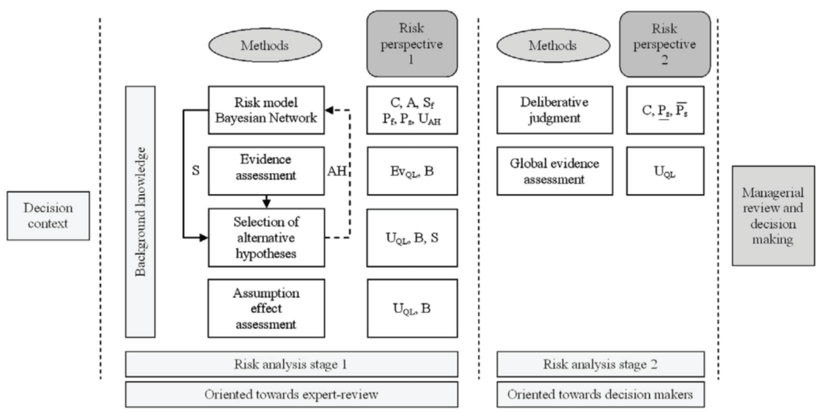



**Figure 9.** Proposed framework for risk analysis of maritime transportation systems. Symbols of the risk perspectives RP1 and RP2 are explained in PIII, from p.43 onwards

[27] The framework is inspired by Aven (2010) and Aven (2013) but is based on a modified risk perspective (including biases), adopts a different method for assessing the evidence and for selecting alternative hypotheses, and is expanded with a second stage.

[28] These tools are inspired by Kloprogge et al. (2011), Zio and Apostolakis (1996) and Aven (2013), but are modified and extended in light of the adopted risk perspective.

In the first stage, a risk model is developed using Bayesian Networks (BN). This (non-predictive) model does not lead to a risk characterisation by itself, but functions as i) an argumentation based on available evidence, ii) a tool for communication between stakeholders, and iii) an aid to thinking.

Model functions i) and ii) are closely connected with the qualitative evidence assessment, in which a set of qualities of the evidence underlying the model construction are judged by an assessor. This provides insight behind the quantification, indicating which parts of the model are well-supported and which are not, which are conservative and optimistic and which to prioritize for further refinement. Together with a sensitivity analysis, this evidence assessment is used for selecting alternative hypotheses for the most important elements, where importance is qualitatively mapped in terms of sensitivity, strength of evidential support and direction of bias. The alternative hypotheses are implemented in the risk model and allow insight in the stability of the risk metric in light of plausible alternative submodels in the Bayesian Network.

Model function iii) takes the model as its object. The fundamental idea is that the model does not directly provide insight in the actual situation being modelled. Rather, it provides insights by revealing key features of its own assumptions, leading to a reflection on behalf of the model user. Thus, the assessor deconstructs the model by identifying assumptions, the effect of which on the model results are argumentatively assessed. Acknowledging the instability of open systems as outlined in Section 4.2.1, these assumptions include the causal relations between the variables in the Bayesian Network model (the arcs) and the parameterization of the probability tables underlying the variables (the nodes). Assumptions can also relate to factors or phenomena not considered in the model. Assumptions are assessed regarding the magnitude and direction of deviation and consequence range where the assumption effect occurs. The strength of justification indicates how plausible the ratings are.

In the second stage, the results of the first stage are taken as evidence for a deliberative uncertainty judgment. An assessor expresses his degree of belief of the consequences considering the evidence of the first stage. Due to the inaccuracy of these beliefs, subjective uncertainty intervals are used. A qualitative assessment of the global strength of evidence accompanies these judgments, providing insight in the confidence the assessor has about these.

The decision making does not follow directly from the risk quantification, but relies on a broad evaluation process where other relevant factors (costs, public and socio-economic concerns) are considered as well.

Compared with the state of art, the framework takes a clearer position in the spectrum of scientific approaches to Risk Analysis, see Figure 3. The risk analysis is primarily “precautionary constructivist with uncertainty evaluation”, as it is the result of a series of judgments by an assessor, broadly considering uncertainties. The precautionary character follows from the explicit attention given to value-laden biases. The framework can also be proceduralist if the judgments in the second stage are made by a wider stakeholder group.

Furthermore, the evidence and assumption assessment schemes contribute to ongoing research on how to characterize uncertainty in risk analyses. Recognizing the previous developments in risk research for tools for characterizing the strength of evidence, uncertainties and biases, e.g. (Aven, 2013; Flage and Aven, 2009; Rosqvist and Tuominen, 2004), the developed tools add to the available methods for this purpose.

### 5.1.2 Application

In PIII, the framework is applied to a case study addressing the accidental risk of ship-ship collisions with oil tankers in the open sea area of the Gulf of Finland. The focus is on the consequences, in particular on the probability of oil spills exceeding certain sizes. Such information is useful to inform response capacity and fleet organization planning, and for ecological risk analysis. Throughout the analysis, a precautionary decision maker is assumed. Details about the model and analysis are found in PIII, from p. 52 onwards.

The BN model integrates ship traffic, tanker layout and vessel dimension data, accident data, ship collision damage models and expert judgments.

The evidence assessment shows that the encounter situation (described through ship traffic and vessel data) is based on strong evidence, whereas the impact situation (mainly based on expert judgment) involves higher evidence uncertainty. The consequence models are based on accepted engineering principles, but are poorly empirically confirmed and involve a conservative bias.

The parameter sensitivity analysis on the BN-model, together with the evidence assessment, is used to identify BN-variables which are prioritized for considering alternative hypotheses. When implemented, the risk model is used to calculate the model-based risk levels, using the alternative hypotheses.

The assumption assessment is used to reflect on the effect of the assumptions on the model results, focusing on the magnitude and direction of deviation and the consequence range where these occur.

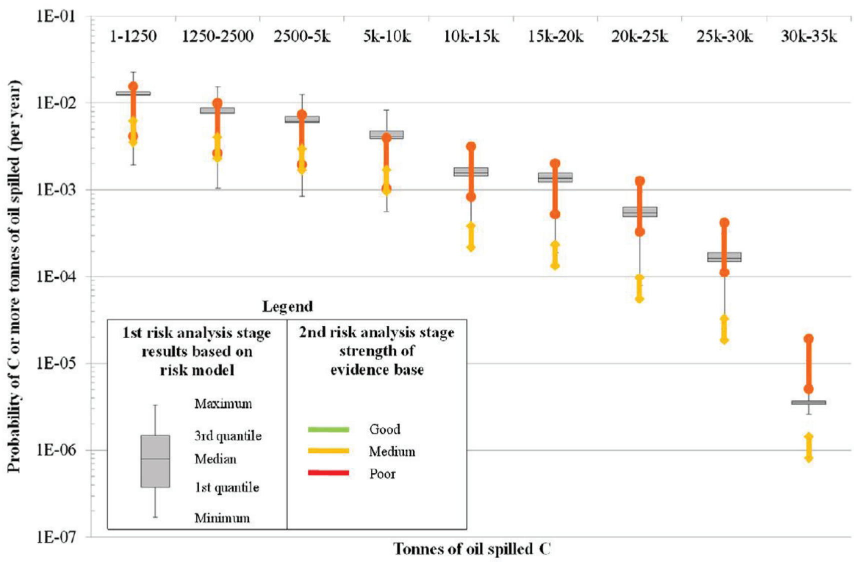



**Figure 10.** Results of the case study using the proposed framework. PIII, p. 51 onwards

In the second risk analysis stage, the information from the first stage is used to make a deliberative uncertainty judgment, using interval probabilities. A colour code represents the overall strength of evidence on which this judgment is based.

## 5.2 Operational risk analysis: risk in collision avoidance context

### 5.2.1 Framework

Understanding risk as in Section 4, the proposed framework for a risk-informed collision alert system (CAS) takes a current situation as its basis for identifying the possibility of ship-ship collision between the "own" and the "target" vessel. The CAS intends to enhance situational awareness, the lack of which has been found to be an important contributing factor to ship collision accidents (Baldauf et al., 2011; Chauvin et al., 2013; Grech et al., 2002).

Figure 11 illustrates the theoretical framework for operationalizing ship-ship collision risk, explained in detail in PIV, from p. 184 onwards.

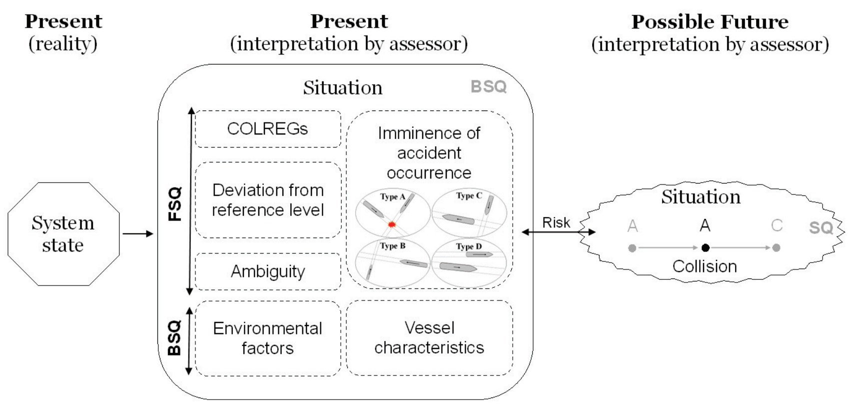



**Figure 11.** Outline of the theoretical framework for operationalizing ship-ship collision risk, based on PIV

In regards the collision risk, the assessor relies on a set of situational qualities (SQs) of a present time to make an interpretation about the possibility of occurrence of a collision event (the focus in a possible future situation). As outlined in Table 6, situations have a complex structure with a foreground, background, focus and horizon. The main challenge in devising a risk-informed CAS is to identify which SQs are primarily relied on for judging the possible collision occurrence. In the framework of PIV, based on expert elicitation, it is taken that four mechanisms underlie the risk judgment. These are the COLREGs[29], which (amongst other) guide the interpretation into a certain encounter type (overtaking, head-on or crossing), the interpretation of the imminence of accident occurrence, of the deviation from a reference level and of the presence of ambiguity.

[29] COLREGS: international regulations for preventing collisions at sea

For different encounter types, the current situation is operationalised through a set of foreground situational qualities (FSQs). These are influenced by certain background situational qualities (BSQs).

The judgmental character of the risk analysis is clear from the fact that the SQs are interpretations by an assessor based on the actual system states[30]. Furthermore, the risk interpretation is contextual in the sense that the SQs can be operationalized differently for different navigational settings. For example, in open sea navigation, the "deviation from reference level" can be that a target vessel navigates closer to the own vessel than would normally be expected in similar encounters, or that the target vessel performs an unexpected turning manoeuvre. In ice convoy navigation, the "deviation from reference level" could be that a target vessel ahead in the convoy suddenly drops its speed.

The risk is measured using a two-stage approach, see Figure 12.

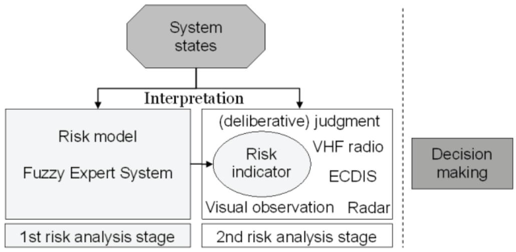



**Figure 12.** Framework for risk analysis in operational collision avoidance context

In the first stage, a fuzzy expert system (FES) based risk model is constructed. This model converts system states to measurements of SQs, which are further combined into a qualitative risk measure. A FES is a modelling tool which can map complex, nonlinear input-output relations in an intuitive and relatively simple manner. An interpretation of the main elements of a FES is given in light of the adopted risk perspective in PIV, from p. 186 onwards.

In the second stage, the risk indicator (i.e. the model output) is considered in a wider context and other information sources are consulted. These include visual observation, information from other technological sources (ECDIS and radar) and communication through VHF radio[31]. Together, these lead to a judgment about the likeliness of ship-ship collision. Based on this judgment, a decision is made about the need to perform collision-avoidance actions.

Thus, the risk model suggests a risk level rather than declaring the situation to be of a certain definite severity. The model is not intended to be used in an automated collision avoidance algorithm, unlike many models suggested in the literature (Statheros et al., 2008; Tam et al., 2009).

The reason for this is that the model only accounts for the main SQs. However, other elements in the situation, e.g. the presence of a recreational vessel, a third vessel in the encounter or a modified navigational status of one of the encountering vessels as signalled by lights and shapes, are not modelled. These SQs may affect the risk judgment and the subsequent decision making.

[30] E.g., a distance (an actual system state) can be interpreted as 'close' by an assessor.

[31] ECDIS: electronic chart display and information system, VHF: very high frequency

### 5.2.2 Application

In PIV, the framework is applied to a case study for an open sea area. The resulting CAS model is schematically shown in Figure 13.

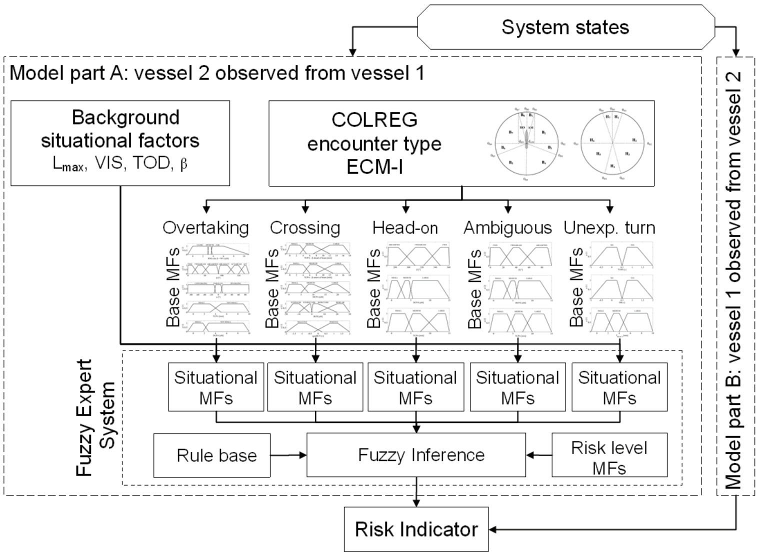



**Figure 13.** Schematic overview of the developed risk-informed CAS, based on PIV

The structure is defined through an expert elicitation process, identifying five structural clusters corresponding to different types of encounters: overtaking, crossing, head-on, ambiguous and encounters with an unexpected turn.

In each of these, different SQs are relied on for interpreting the possible collision occurrence. The Analytical Hierarcy Process (Saaty, 1980) is used to elicit which FSQs are relied on for making the risk interpretation, and which BSQs influence the interpretation of the FSQs.

The discretization and parameterization of the baseline categories of the SQs, i.e. the membership functions (MFs) of the variables of the FES, is based on an expert elicitation procedure proposed by Cornelissen et al. (2003). These baseline MFs are modified into situational MFs based on the values of BSQs.

Using the rule base, these situational MFs are linked to an appropriate ordinal risk level (safe, caution, warning and alarm), which are given an interpretation relevant for navigational operations, see PIV, p. 188.

As outlined in Section 4.3, uncertainties and biases need to be addressed. In PIV, the evidential qualities of the data, expert judgments, models and assumptions are qualitatively rated separately for the model structure, content, discretization and parameterization.

Other uncertainties requiring attention (and possibly leading to modifications to the model) before implementing the system in practice include: i) the plausibility of the reduction of actual encounters to pairwise encounters, ii) the number of alarms raised by the CAS compared with currently applied methods, iii) the existence of possible risk-compensating behaviour and risk migration due to the use of the model, and measures to counteract these effects.

# 6. Evaluating risk models and analyses

This chapter addresses Objective 5 of Section 1.2, and research question 4. of Section 3.3. It provides an integrated view on the issue of evaluation of risk models and analyses, which combines the approaches taken in PIII and PIV. The reason for combining these in an overarching framework is that while the risk models are used differently (in PIII the entire model is subject to scrutiny in its use phase, in PIV only the output is used), the main characteristics of evaluating the risk model are very similar. The **main novelties** are:

- a discussion on the nature of evaluation in risk analysis[32];
- a framework including criteria to establish credibility of risk models and analyses, based on the principles of Section 4 [PIII,PIV][33].

## 6.1 Evaluation (not validation) of a risk model/analysis

Debates about the nature of validation in science cannot be seen separate from an underlying adherence to fundamental theories of knowledge: what is knowledge and what constitutes confirmation of a knowledge claim? Barlas and Carpenter (1990) describe two major paradigms in the philosophy of science addressing these questions: the logical empiricist/reductionist school and the functionalist/holistic school[34].

According to the former paradigm, knowledge is an entirely disinterested, universal, asocial, acultural, value-free “truth”. Utilizing the metaphor “mirror of nature”, such philosophies consider knowledge as the reflection of nature on an “unclouded mirror”. The latter paradigm takes knowledge to be socially justified belief rather than a product of mirroring nature. Knowledge is a type of assertion warranted because of the arguments given to support it rather than because of an absolute external standard. Knowledge is socially, culturally and historically embedded, lacking neutral foundations.

[32] This issue is not covered explicitly in the publications, but is elaborated upon to understand the principles underlying the evaluation framework.

[33] The framework is mainly based on the ideas discussed in PIII, p. 53 onwards. It is extended to account for the different model uses of PIII and PIV, more clearly distinguishing model structure, content, discretization, parameterization and behavior.

[34] Clearly, the reduction to two paradigms is a rough simplification as many theories exist, see e.g. Lemos (2007) for an overview. The analysis by Barlas and Carpenter (1990) is followed as it is considered sufficiently distinctive for the current purposes, and because it is broadly in line with the realist-constructivist distinction made by e.g. Bradbury (1989), Shrader-Frechette (1991), Thompson and Dean (1996) and Hermansson (2012), see Section 2.1 and Publication I.

Under a logical empiricist/reductionist philosophy of knowledge, validation is seen as a strictly formal, algorithmic, "confrontational" process. As the model is taken as an objective and absolute representation of the modelled system, attempts at revealing its truth are focused on confronting the model with empirical "facts"[35]. In a functionalist/holistic view, validation becomes a semi-formal, conversational process. Models are not true or false, but can be more or less useful: model validation is a process of building confidence in the model's usefulness. Hence, this becomes a conversational matter, where argumentative justification rather than algorithmic procedures take centre stage.

In Section 4.1, a constructivist understanding of the risk concept has been adopted, where risk is not an objective reality existing as an inherent part of a system, but rather something attributed to a system by an assessor in terms of a possibility. Due to violation of the constancy requirements and the empirical testability of risk models in complex socio-technical systems such as the maritime transportation system (see Section 4.2), it is proposed to use risk models heuristically, as a guide in inquiry rather than as a reflection of an underlying truth. The intended use of risk models is argumentatively and suggestively, as a basis for communication and as an aid to thinking (both in the policy-oriented and operational risk analyses).

From this, it is evident that for the developed risk analysis frameworks of PIII and PIV, validation is to be understood in line with the functionalist/holistic view. Focus is on conversationally establishing that the models can be used as intended. Correspondingly, model evaluation is taken as a formative, rather than summative process, i.e. the evaluation should contribute to the reflection of the risk analysts and reviewers of risk analyses (peers and stakeholders) rather than to declare the analysis to be of a certain standard, a view shared by Busby and Hughes (2006).

Furthermore, in Section 4.2.3, it is argued that a broad uncertainty and bias evaluation is needed. Thus, rather than being *validated*, risk models are *evaluated*. As noted by Oreskes (1998), evaluation implies an assessment in which both positive and negative results are highlighted, where the grounds on which a model is declared good enough for its purpose are articulated while openly acknowledging uncertainties[36].

## 6.2 Evaluation of a model-based risk analysis: framework

### 6.2.1 General outline

In the frameworks of PIII and PIV, the risk model and the risk analysis are distinguished, the former being a part of the latter. Mechanisms are required

[35] An approach along these lines in the context of waterway risk analysis is taken e.g. by Friis-Hansen and Simonsen (2002), Weng et al. (2012) and Mulyadi et al. (2014), where the model output is compared with historical data as (the only) validation method.

[36] Oreskes et al. (1994) provide further definitions, clarifying the distinctions. Verification (from Latin *verus*: true) is the process of establishing truth. Validation (from Latin *validus*: strong) does not necessarily establish truth, but is a process of establishing legitimacy. Evaluation (from French *évaluer*: to find the value of) is a process of appraising or valuing.

for looking beyond the model-based results. In PIII, this is performed through an evidence and assumption assessment. In PIV, other means of observation are used during the model use phase, while an evidence assessment and uncertainty identification process highlight further research directions in the model development stage.

A central issue in the evaluation is the intended use of the model, see Section 4.2.2 and 4.2.3. In PIII, the model is a communication tool which puts forward an argumentation, which is scrutinized through an evidence and assumption assessment scheme to arrive at a risk judgment. In PIV, the model suggests an alert level to the system user, who seeks other information to judge the risk.

Figure 14 shows the conceptual framework for evaluating policy-oriented and operational risk analyses, combining the ideas of the risk model/analysis evaluations performed in PIII and PIV. Table 8 contains the specific evaluation criteria for the different aspects.

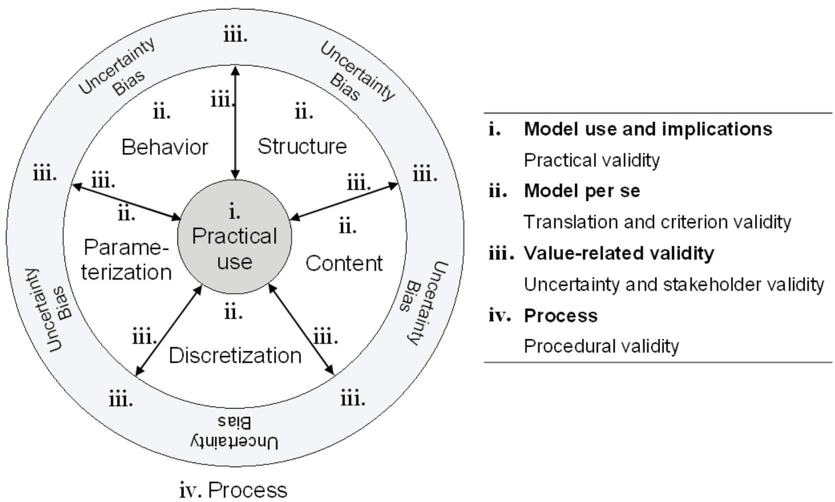



**Figure 14.** Framework for evaluating risk models and analyses, integrating ideas of PIII and PIV

The framework integrates a number of ideas from various sources and disciplines[37]. The focus is on the intended practical use of the model (item i.), following ideas of Hodges and Dewar (1992). Certain further usability criteria are identified: the interpretability of the numbers (Aven, 2011b) and the focus on observable quantities (Aven and Heide, 2009)[38]. The evaluation of the model

[37] These include operations research (Hodges and Dewar, 1992), social sciences (Trochim and Donnely, 2008), systems dynamics modelling (Forrester and Senge, 1980), and modeling with expert systems (Pitchforth and Mengersen, 2013). Relevant sources from within Risk Analysis are included as well (Aven and Heide, 2009; Rosqvist and Tuominen, 2004). While various elements of the framework are known in other research communities, the framework has to the best of the author's knowledge not been presented in an integrated manner in the Risk Analysis discipline.

[38] In Aven and Heide (2009), this concerns whether uncertainties are assessed about observables, or about model parameters. The assignment of subjective uncertainty intervals to model

*qua* model (item ii.) combines ideas from Forrester and Senge (1980), Trochim and Donnely (2008) and Pitchforth and Mengersen (2013). The consideration of uncertainties and biases (item iii.) is included in the evaluation framework based on ideas from Rosqvist and Tuominen (2004) and Aven and Heide (2009). The importance of procedural aspects of the risk analysis (item iv.) is based on Rosqvist and Tuominen (2004) and Aven and Heide (2009).

### 6.2.2 Specific evaluation criteria

Table 8 lists the four identified evaluation aspects of Figure 14, considered separately for policy-oriented and operational uses as needed. Each aspect is further split into different evaluation criteria, which are given a name and which are further concretized by formulating a question which aids in establishing credibility. The sources on which the proposed criteria are based are indicated as well.

The focus is on the model use (item i.), which implies that different criteria are applied for the models of PIII and PIV. Both models are intended as aids to communication and can be evaluated by ascertaining that these indeed assist in communication. The model of PIII is used as a policy-support tool, and can be evaluated in terms of its ability to assist decision making, whether the recommendations are sensitive to the identified model scope, structure, content, discretization and parameterization and whether the implementation of the recommendations improves system performance. The model of PIV is used to provide alerts, and can be evaluated by ascertaining if the alerts are timely and parsimonious. It can also be evaluated by identifying the model's ability to assist decision making and by reducing the number of collisions.

The evaluation of the model *qua* model (item ii.) focuses on model structure, content, discretization, parameterization and behavior. Considering these aspects in turn creates a platform for systemizing the formative, conversational process of argumentative reflection about the model as an adequate tool for aiding an assessor in making a risk judgment. For each element, various criteria/tests are identified, see Table 8. These aspects can be understood in terms of the concept of the operationalization of a construct, see Trochim and Donnely (2008). This concerns how the mental construct (the conceptual level) is transformed to a model construct (the measurement level). This is split into translational validity (how well the mental construct is translated in a model) and criterion validity (how well the model scores in certain tests). Translation validity consists of face and content validity, whereas criterion validity consists of concurrent, convergent and behaviour validity[39]. These are outlined below and concretized in specific criteria in Table 8.

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parameters has been criticized by e.g. Apostolakis (1990) because of the difficulty in explaining what exactly the assessor is uncertain about and what the uncertainty interval means.

[39] Trochim and Donnely (2008) and Pitchforth and Mengersen (2013) also consider discriminant validity, i.e. the degree to which the measurement/model appropriately differs from measurement/models describing another system. As this is considered of too little added value in an evaluation exercise, this is not retained here.

Face validity refers to a subjective interpretation of the relevance and quality of the model in relation to the concept it intends to measure. For example, when considering the tanker oil spill risk, it can be checked that the tank sizes are considered in the model.

Content validity concerns a more careful judgment about the relevance and completeness of the elements included in the model in relation to the system it intends to describe. For example, each variable can be considered in turn, where its underlying rationale and its relations to other variables are scrutinized, which may expose assumptions relevant to consider.

Concurrent validity refers to how the model compares with other models for the same system. For example, the elements and relations considered in an oil spill risk model for a waterway area can be compared with other models for this purpose. Such a comparison can elucidate discrepancies, which can increase the credibility of the model, or highlight uncertainties and assumptions.

Convergent validity addresses how the model compares with other models for similar systems. For example, the elements considered in a ship collision risk model can be compared with a risk model for road traffic collisions. This can increase, on a more distal level, the confidence of the model's plausibility.

Behaviour validity concerns a number of specific tests, e.g. questioning whether the model response is qualitatively in line with expectations and whether the model behaviour is sensitive to elements to which the system is expected to be sensitive to.

All above listed model evaluation aspects can be used to increase the confidence in the model as an appropriate representation of the addressed phenomenon. Simultaneously, these can also be used to highlight uncertainties and biases beyond the model, in line with item iii. of the risk analysis evaluation framework.

As mentioned above, in the framework of PIII, these uncertainties and biases (considered by alternative hypotheses, evidence assessment or an assumption assessment) are used in and alongside the model to arrive at a risk judgment. The biases in the model need to be in accordance with stakeholder values. In the framework of PIV, the uncertainties need consideration before implementing the model in practice while the biases need to be in line with the non-epistemic aims of the model, i.e. stakeholder values need to be appropriately reflected. This last issue relates to the need to provide sufficient and timely alerts, while minimizing the number of alerts raised, as these are often considered a nuisance (Baldauf et al., 2011).

The procedural aspects of the risk analysis (item iv.) concern whether the evidence and the model construction are transparent. Finally, it can be evaluated whether the expert elicitation (subjective probabilities in PIII, fuzzy membership functions in PIV) are based on accepted expert elicitation procedures. Relevant guidelines in Cornelissen et al. (2003) and Aven and Heide (2009) are referred to.

**Table 8.** Evaluation framework and criteria, elements from Figure 14

| **i. Model use and further implications** | | | **Ref.** | **Tested** | |
|---|---|---|---|---|---|
| ***Policy-oriented*** | | | | **PIII** | **PIV** |
| OBS | Observability | Does the analysis focus on observable system qualities or on model parameters? | AH | Y | N/A |
| INT | Interpretability | Can the produced numbers be given an interpretation? | A1 | Y | N/A |
| COM | Aid to communication | Does the model help the communication between assessors/stakeholders in the deliberation phase? | HD | N | N/A |
| PS | Policy sensitivity | If the model scope, structure, content, discretization or parameterization is changed, do the policy recommendations change significantly? | FS | N | N/A |
| SI | System improvement | Are the provided results helpful to decision makers? When applied, is the system performance improved? | FS | N | N/A |
| ***Operational*** | | | | | |
| TA | Timeliness of alerts | Are the alerts provided in a timely manner? | - | N/A | Y |
| PA | Parsimony of alerts | Is the number of alerts adequate? Is the number of unnecessary alerts minimal? | - | N/A | N |
| INT | Interpretability | Can the produced numbers be given an interpretation? | A1 | N/A | Y |
| COM | Aid to communication | Does the model assist in the communication between operators to form a risk judgment? | HD | N/A | N |
| SI | System improvement | Are the alerts considered useful in decision making? Does the model help to reduce the number of collisions? | FS | N/A | N |
| **ii. Model per se** | | | | | |
| ***Structure*** | | | | | |
| FV | Face validity | Does the model structure seem like a plausible representation of the conceptual construct? | TD PM | Y | Y |
| CV | Content validity | Do the relationships between model elements and variables correspond to how the corresponding factors in the conceptual construct are related? | TD PM | Y | N |
| CCV | Concurrent validity | Does the model structure correspond to that of another model for the same problem in the same system? | TD PM | Y | Y |
| CVV | Convergent validity | Does the model structure correspond to that of a model for a comparable problem in a similar system? | TD PM | N | N |
| BA | Boundary adequacy | Are the model elements aggregated in an appropriate manner? Are the structural relations at the interfaces between submodels adequate? | FS | N | N |
| ***Content*** | | | | | |
| FV | Face validity | Do the model elements seem to adequately represent the conceptual construct? | TD PM | Y | Y |
| CV | Content validity | Does the model contain the most relevant factors relevant to the conceptual construct? | TD PM | Y | Y |
| CCV | Concurrent validity | Does the model (or its submodels) contain the same elements as another model for the same problem? | TD PM | Y | Y |
| CVV | Convergent validity | Does the model (or its submodels) contain similar elements as a model for a similar system? | TD PM | N | N |
| ***Discretization (of nodes of a BN or MFs of a FES)*** | | | | | |
| FV | Face validity | Is each variable discretized into states which look plausible to experts? | TD PM | N | N |
| CV | Content validity | Is each variable discretized into states which correspond to the full range the variable can adopt? | TD PM | N | N |
| CCV | Concurrent validity | In another model for the same problem in the same system, are similar variables similarly discretized? | TD PM | N | N |
| CVV | Convergent validity | In a model for a comparable problem in a similar system, are similar variables similarly discretized? | TD PM | N | N |
| DC | Dimensional consistency | Are all possible states included in the discrete states of the variable? | FS PM | Y | Y |
| ***Parameterization (probabilities, parameters of MFs, other factors)*** | | | | | |
| FV | Face validity | Do the parameters in the model look plausible to the experts? | TD PM | N | N |
| CV | Content validity | Do the parameters adequately reflect the background knowledge? | TD PM | N | N |
| CCV | Concurrent validity | In another model for the same problem in the same system, do the parameters have comparable values? | TD PM | N | N |
| CVV | Convergent validity | In a model for a comparable problem in a similar system, do the parameters have similar values? | TD PM | N | N |
| DC | Dimensional consistency | Are the units for the parameters in the model dimensionally compatible? | FS | Y | Y |
| ***Behaviour tests*** | | | | | |
| BST | Behaviour sensitivity | Is the model sensitive to structural relations and/or parameters to which the conceptual system would also be? | FS | Y | N |
| QFT | Qualitative features | Does the model qualitatively respond to hypothesized variable states as the conceptual system would? | FS | Y | Y |
| ECT | Extreme conditions | Does the model respond to hypothesized extreme variable states as the conceptual system would? | FS | Y | N |
| CCV | Concurrent validity | When the model is run, are the output states comparable to those of other models? | TD PM | Y | Y |

| | | | | | |
|---|---|---|---|---|---|
| **iii. Value-related validity** | | | | | |
| ***Uncertainty*** | | | | | |
| AH | Alternative hypotheses | Are alternative structural relations, discretizations or parameterizations assessed by alternative hypotheses? | AH ZA | Y/N | N |
| AS | Assumptions | Are assumptions in and beyond the model identified and their effects on the model output assessed? | AH A2 | Y | Y |
| EVI | Evidence | Is the evidential strength assessed and areas for improvement identified? | AH FA | Y | Y |
| OUT | Outcome | Are additional outcome uncertainties identified? Are the effects on the model outcome assessed? | AH FA | Y | N |
| ***Bias*** | | | | | |
| VAL | Stakeholder values | When value-laden choices are needed in the analysis, are stakeholder values appropriately reflected? | RT | Y | N |
| EVI | Evidence | Are evidential biases assessed? | RT | Y | Y |
| OUT | Outcome | Is the effect of evidential biases on the model outcome assessed? | RT | Y | N |
| **iv. Process** | | | | | |
| EE | Expert elicitation | Is the expert elicitation based on accepted procedures and guidelines? | AH | Y | Y |
| TR | Transparency | Is the model construction and underlying evidence transparent? | RT | N | N |

A1 = Aven (2011b) | A2 = Aven (2013) | AH = Aven and Heide (2009) | FA = Flage and Aven (2009) | FS = Forrester and Senge (1980) | HD = Hodges and Dewar (1992) | PM = Pitchforth and Mengersen (2013) | RT = Rosqvist and Tuominen (2004) | TD = Trochim and Donnely (2008) | ZA = Zio and Apostolakis (1996) | Y = assessed in the Publication | N = not assessed in the Publication

## 6.3 Examples from the risk analysis applications

In Table 8, it is shown which evaluation tests have been applied to the applications developed in PIII and PIV. For PIII, examples are found from p. 54 onwards. For PIV, this is from p. 192 onwards.

While the framework is constructed with BNs and FESs as modelling tools, it is plausible to assume that the framework (or elements thereof) can also be useful for evaluating risk analyses using other modelling techniques. This is clear from the discussions made in the appendix of PI from p. 128 onwards, where various criteria of the evaluation framework are applied to maritime waterway risk models which apply different modelling tools.

For example, the interpretability of the risk numbers has been considered in the three example applications discussed in PI from p. 128 onwards, where it is found that the produced numbers cannot always be meaningfully interpreted. This can be problematic, as it may be difficult to explain what exactly has been measured in the analysis.

In one of the applications (PI, p. 130), the dimensional consistency test is applied, finding that the model discretization is made in such a way that the risk seems larger in certain sea areas than in others. However, upon application of this test, it is found that the reason for this discrepancy in risk levels may be significantly affected by the choice of the size of the sea areas. Hence, the measured parameters are not dimensionally comparable for the areas. This leads to uncertainty about the conclusions made in the analysis.

In another application (PI, p. 131), the content validity criterion is applied to the model structure of the vessel conflict operator, where it is argued that the structural relations between TCPA and DCPA are incorrectly accounted for in the model[40]. This is supplemented by a qualitative features test, which shows

[40] TCPA: time to closest point of approach, DCPA: distance at closest point of approach

that two scenarios, which should lead to a different risk level, are not discriminated as such by the model. Hence, these tests are found helpful to highlight uncertainties in the model.

Overall, these examples and the examples shown in PIII and IV show that the evaluation criteria of the framework can increase confidence in the risk models, and/or elucidate uncertainties in risk models. Depending on the intended model use in the risk analysis, this can act as a basis for forming an informed judgment about risk (PIII) or to identify focus areas for further research (PIV).

# 7. Conclusions and future work

The overall aim of this thesis has been to contribute to a number of foundational issues of Risk Analysis within the application area of maritime transportation, answering calls to extend such research to application areas.

PI has shown that Risk Analysis faces a number of challenges to its scientific foundations. Unlike earlier research, which has addressed these issues on a theoretical level, this has been approached through analysing applications and through case studies. This is believed to be more directly beneficial for spurring research and discussion on foundational issues within the specific application areas in focus in this thesis.

The analysis of risk definitions and perspectives and scientific approaches in PI confirms the existence of a rather chaotic situation in the discipline, as argued e.g. in Aven (2012a). Many risk definitions co-exist, while these do not necessarily provide insight in the adopted scientific approach (realist, constructivist or proceduralist). Most work in the waterway risk analysis applications applies some form of the prototypical realist approach, with a focus on the calculated probabilities/numbers, which are based primarily or exclusively on data and mathematical/engineering models. Constructivist and proceduralist approaches are found as well, but represent a minority. PI also shows the close relation between the adopted definition and perspective, and illustrates the lack of uncertainty treatment in applications.

The case studies of PII and PIV provide evidence for the theoretical discussions in Aven and Heide (2009) that risk analyses in general are not reliable tools for informing a decision.

The above findings, corresponding to Objectives 1 and 2 as stated in Section 1.2, lead to the need to clarify a number of principles. First, a terminological-conceptual basis is needed, clarifying how risk is understood, how it relates to other concepts, and which implications this understanding has. Second, a reasoned argument is needed how risk models, if not reliable, can be used. Third, consideration is needed as to how to evaluate risk models and analyses.

The above issues have been addressed in Objective 3 to 5, covered in PIII and PIV. Two frameworks for risk analysis have been proposed, for policy-oriented maritime transportation risk analysis and for risk analysis in a collision avoidance context. The former is a quantitative risk analysis framework applying Bayesian Networks as a modelling tool; the latter a qualitative framework applying Fuzzy Expert Systems. A risk analysis evaluation framework integrating the approaches to evaluation in PIII and PIV is presented.

Future research on risk analysis in maritime transportation can take several directions, both concerning applications and related to more theoretical issues.

First, the presented frameworks can be applied to other accident types, and models for the presented applications further improved. For the oil spill risk model, more advanced collision damage and oil outflow models could be used, to shed light on the temporal progression of the oil spill, considering subsequent hull damage. For the collision alert system, research can be performed to strengthen the evidence base, to address the uncertainties mentioned in Section 5.2.2, and to develop alert systems in other navigational environments (port waters, harbour approaches, specific environmental conditions).

Second, additional frameworks for risk analysis in maritime transportation can be developed, based on other modelling tools and approaches. For example, PI shows that relatively little work has been performed to define maritime transportation risk indicators. Further research on defining appropriate indicators and on how to integrate these in a framework to monitor and mitigate transportation risk could be undertaken. It is also worth exploring the possibilities of new systemic accident theories in the context of waterway risk analysis. The merits and challenges of proposed frameworks could be investigated.

Third, the research on principles and frameworks for risk analysis could be extended to other maritime applications. Psaraftis (2012) identifies a number of issues requiring research in the context of Formal Safety Assessment. The feasibility of applying relatively recently proposed uncertainty-based risk perspectives (Aven, 2013; Aven, 2011) in the ship design process and in the context of goal-based standards could be investigated.

Fourth, there is much room for additional research and discussion on the evaluation/validation of risk analysis. As found in Section 2.2.3, very little systematic research has been dedicated to this issue. The contributions made in this thesis could be discussed, further developed/adjusted and applied.

Finally, there is a long list of foundational issues in the general Risk Analysis discipline which could be approached within the maritime application area. Aven and Zio (2014) list 10 main scientific issues needing further research, including concepts/terminology, methods for representing uncertainty, causality in a risk analysis context, the relation between risk analysis and values, how to represent risk information and how to use risk analyses in different decision making contexts. These authors furthermore identify more than 20 questions which would benefit from future scientific attention. Many of these are relevant as well to the maritime application area and correspond to the issues identified by Psaraftis (2012) in the context of Formal Safety Assessment.

It is clear that the list of future research is very extensive, which corresponds to the position taken in the introduction that Risk Analysis is an unsettled scientific discipline.

The primary motivation of the research performed in this thesis is to establish that the maritime application area would, as the general discipline, benefit from increased attention to and scientific research on foundational issues. To the extent the proposed principles, frameworks and tools for evaluation contribute to this end, the general aims of the work have been achieved.

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# Errata

**Publication I**

On p. 131, Section A.3., first paragraph: “Finally, the collision probability $P_x(A)$ is mathematically derived from the fitted distribution $f((A4))$ […]” should read “Finally, the collision probability $P_x(A)$ is mathematically derived from the fitted distribution $f(C'_{max})$ […]”.

**Publication IV**

On p. 187, Section 4.3.1., fourth paragraph: “As the measurement procedure does not necessarily result in the same calculated risk level for each vessel, maximum risk is adopted level for both vessels […]” should read “As the measurement procedure does not necessarily result in the same calculated risk level for each vessel, the maximum risk level is adopted for both vessels […]”.

On p. 188, Section 4.3.2., second paragraph: “The elements of $w$ reflect relative importance […]” should read “The elements of $w$ reflect the relative importance […]”.

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Risk analyses are widely used tools for decision support. Nonetheless, the risk analysis discipline has received much criticism. Calls have been made for increased focus on foundational issues, both in the general discipline and in application areas.

Answering these calls, this thesis investigates and proposes a number of risk analysis principles, addressing concepts and terminology, risk model reliability, risk models and prediction, risk model use and the consideration of uncertainty and bias. The principles are used as a basis for developing two risk analysis frameworks: one for policy-oriented and one for operational maritime risk analysis. Finally, the evaluation of risk models and analyses is addressed, focusing on the issue of credibility of a risk analysis.

Principles, frameworks and evaluation are investigated and exemplified through applications concerning accidental risk of maritime transportation.

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